BREAKTHROUGHS IN LOW-PROFILE LEAKY-WAVE HPM ANTENNAS

Prepared by: Robert A. Koslover (PI), Greg R. Raith, and Sammuel M. Jalali

Scientific Applications & Research Associates, Inc.
6300 Gateway Drive
Cypress, CA 90630-4844

21 Mar 2016

Data Item: A002 - Progress, Status, & Management Quarterly Report #10

Prepared for:

Program Officer: Lee Mastroianni
ONR Code 30

OFFICE OF NAVAL RESEARCH
875 North Randolph Street
Suite 1425
Arlington, VA 22203-1995

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
21-03-2016

2. REPORT TYPE
Quarterly

3. DATES COVERED *(From - To)*
19 Dec 2015 – 20 Mar 2016

4. TITLE AND SUBTITLE
Breakthroughs in Low-Profile Leaky-Wave HPM Antennas
Progress, Status, & Management Report
(Quarterly Report #10)

5a. CONTRACT NUMBER
N00014-13-C-0352

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Koslover, Robert A.; Raith, Greg R.; Jalali, Sammuel M.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Scientific Applications &
Research Associates, Inc.
6300 Gateway Drive
Cypress, CA 90630-4844

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
875 North Randolph Street
Suite 1425
Arlington, VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)
Code 30

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Distribution Statement A. Approved for public release; distribution is unlimited. Other requests for this document shall be referred to the Program Officer listed in the contract.

13. SUPPLEMENTARY NOTES
..

14. ABSTRACT
This report describes progress during the 10th quarter of this program and highlights the current status of the research. Activities this period included continuation of the investigation into improved design methods/recipes for the AAWSEA, presentation of our latest work at the DEPS 18th Annual Directed Energy Symposium, and identification of novel applications and extensions to this technology.

15. SUBJECT TERMS
Leaky-wave Antennas. High Power Microwaves (HPM) Antennas. Low-profile Conformal Antennas.

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
					Lee Mastroianni
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (incl. area code)
Unclassified	Unclassified	Unclassified	SAR	____	(703) 696-3073

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

Table of Contents

List of Figures

1. INTRODUCTION

This is SARA's 10^h Quarterly Report for "Breakthroughs in Low-profile Leaky-Wave HPM Antennas," a 37-month Basic Research effort sponsored by the US Office of Naval Research (ONR). This work includes fundamental theoretical analyses, numerical modeling, and related basic research. Objectives include to discover, identify, investigate, characterize, quantify, and document the performance, behavior, and design of innovative High Power Microwave (HPM, GW-class) antennas of the *forward-traveling, fast-wave, leaky-wave* class.

1.1. Overview of Previous Activities (1st thru 9th Quarter)

During the *first* quarter, we prepared and established useful equations and algorithms for predicting reflections and transmission of incident TE waves from parallel-wire grills, dielectric windows, and combinations of wire grills with dielectric windows, in problems reducible to purely H-plane (2D) representations. We then applied this theory to guide the design of high-gain configurations (again, limited to 2D, H-plane representations) for linear, forward traveling-wave, leaky-wave antennas. The theory built upon equivalent circuit methods and wave matrix theory, which provided useful formalisms upon which we continue to build.

During the *second* quarter, we pursued initial extensions of the previous work into three dimensions, in order to include phenomena with E-plane dependencies. We succeeded in adding into the wave-matrix formalism the reflection/transmission properties associated with the transition to free space from a *finite-width* leaky-wave channel, including the edge-tapering essential to HPM applications. These geometric aspects do not arise in analyses confined to the H-plane alone. Our 3D analyses were somewhat more reliant on numerical models than in the 2D analyses, due to the greater complexity of identifying and/or building practical analytic approaches capable of addressing true 3D geometries of interest.

During the *third* quarter, we explored channel-to-channel coupling (aka, mutual coupling) which (as we have noted earlier) is an important design concern, since it can impact antenna performance significantly in terms of gain, peak power-handling, and impedance matching. Our approach leveraged mostly numerical methods, along with some intuitive arguments, as we explored designs exhibiting different degrees of mutual coupling between adjacent channels. As past and current antenna literature attest, mutual coupling analyses are non-trivial; suffice to say, there is still much work to be done in this area.

During the *fourth* quarter, we continued to study and employ wave-matrix based methods, but with less success than before in applying this approach to *improve* or *optimize* the initial designs. The formalism itself is still valid, but offers reduced practical rewards once an *initial* (i.e., not fully-optimized) geometry (e.g., grill, window, channel depth, etc.) is derived from the more basic-level principles. At that stage, we are finding that further optimization is currently best proceeding via numerical means. Additional work in the fourth quarter led us to identify *new aperture geometries* of potentially-significant practical value, which included the "BAWSEA" and "GAWSEA". These configurations may significantly extend the utility of leaky-wave antenna technology to support integration on more challenging platforms.

During the *fifth* quarter, we designed, analyzed, and documented representative high-performance FAWSEA and CAWSEA antennas suitable for designation as "standard" or "recommended." The configurations we described were scalable with wavelength. These are the initial entries in a library of antennas that will continue to be built throughout this program.

During the *sixth* quarter, we performed additional investigation of designs to support the newer curved apertures, especially the "Bent Aperture Waveguide Sidewall-emitting Antenna" (BAWSEA). We presented this work at the 17th Annual Directed Energy Professional Society (DEPS) Symposium in Anaheim, CA, on March 4th, 2015. Our full slide presentation, entitled "Advances in Low-Profile Leaky-Wave Conformable Antennas for HPM Applications," was included in the unclassified proceedings CD that was recently distributed by DEPS to all the conference attendees.

During the *seventh* quarter, we investigated RAWSEA design considerations and showed that the angle of rotation between the leaky wave channels and the aperture can be understood in terms of an equivalent linear (non-rotated) displacement, an interpretation which helps to guide application of the wave-matrix formalism. However, more work is still needed to speed-up the RAWSEA design process.

During the *eighth* quarter, we identified, investigated, and applied a seemingly-simple but clarifying wave-mapping methodology, which provided improved guidance in making optimal use of generally curved platform surfaces. Following this process helps guide the designer toward a solution that provides both higher gain and greater peak power handling. Via this approach we identified and reported a notable success with the design of an improved CAWSEA that can deliver superior gain, yet still conform to the same radius cylinder as our earlier-suggested “standard/recommended” design.

During the *ninth* quarter, we developed/extended the ray-based analyses to the AAWSEA configuration, employing an analytic parameterization of the inner-curve (channel back-wall) and outer-curve (vicinity of the leaky-grill wall) ogives, while tracking the varying angles of reflection sequentially along the perspective leaky guide, and ultimately adjusting these curves to yield the desired output beam. The approach offered insight, but did not lead us to design recipes with a practical utility comparable to those for the FAWSEA or CAWSEA. We are continuing work in this area.

For more information, we encourage the reader to refer to our earlier *Quarterly Reports #1* thru *#9.*

1.2. Overview of Recent Activities (10th Quarter)

Recent activities included continuation of the investigation into improved design methods for the AAWSEA, presentation[1] of our latest work at the DEPS 18th Annual Directed Energy Symposium, and exploration of new and novel applications/extensions to this technology.

In regard to *applications*, we report (included in our presentation at the DEPS Symposium) the potentially advantageous use of GW-capable FAWSEA or CAWSEA-type antennas as *feeds* to drive larger *conical* dish reflectors. This combination results in *increased gain* (compared to the feeding antennas used in stand-alone configurations) while also providing *superior peak power-handling,* compared to similar-size parabolic reflectors fed by necessarily-smaller horn-type feeds. Next, combining a FAWSEA/CAWSEA feed with a *conical* trans-reflector and a flat twist-reflector (this configuration is now patent pending) yields, to the best our knowledge, *the world’s first and only <u>GW-class</u>, <u>fully-steerable,</u> <u>high-gain</u> antenna*.

As an *extension* to the current leaky-wave antenna research, we are exploring ways to *suppress beam-scanning* with frequency. Recall that unwanted beam-scanning poses a serious limitation on the use of these antennas with *broader-band* HPRF sources. For these, a nearly frequency independent beam-direction is needed to maximize overall RF power on target. Although frequency-scanning behavior is *fundamental* to all continuous-aperture, fast traveling-wave, leaky-wave antennas, we can potentially compensate and redirect/stabilize the beam-direction by adding special structures beyond the leaky-wave interface. We provide a proof-of-principle example in this report, illustrated via a 2D model. However, the geometry in this example is not compact. Practical realization of such a compensation trick within a geometry that *retains the low-profile/packaging* advantages of these antennas may ultimately prove difficult to achieve, but it is definitely a worthy goal.

Further information about the aforementioned new and recent activities is provided in Section 3.

[1] The slides we presented at DEPS 2016 are included in this report (Section 3.3) for convenient reference.

2. STATUS OF THE PLAN/SCHEDULE AND FUNDING

Figure 1 (next page) maps out the updated program plan, for quick reference. The subject contract was awarded on 9/18/2013 and has an end date of 10/17/2016. The total contract value is $868,350, all of which has been authorized per P00006, dated 6/23/2015. According to SARA's accounting system, as of March 18, 2016, expenses and commitments (including fee) totaled $706,912, thus leaving $161,438 in available funds. If one simply compares the calendar and spending on this project, we have now consumed both 81% of the calendar and 81% of the total contract value.

We thank ONR for continued support of this project. There are no new significant technical, schedule, or funding-related program problems to report at this time.

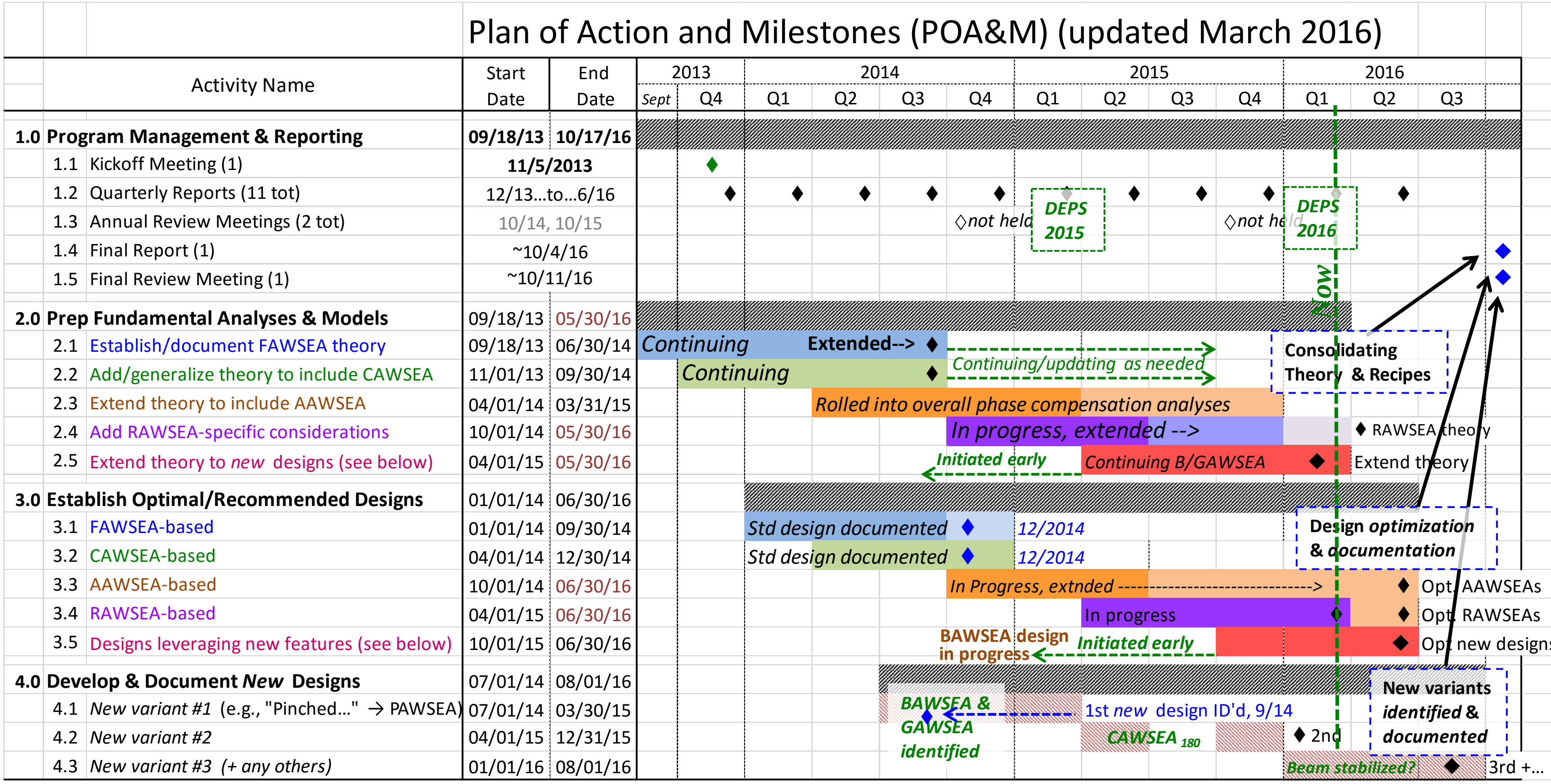


Figure 1. Updated Program Plan

3. RESEARCH AND ACTIVITIES PERFORMED THIS PERIOD

3.1. Status of AAWSEA design recipe development

As previously reported, we have been preparing/improving an evolving set of MatLab scripts to generate suggested/candidate values of wire size & positions and wall curvatures for a "simple" window-less 2D AAWSEA, starting with user-inputted values of the desired antenna length, curvature, center operating frequency, and desired output beam-angle relative to the initial normal. However, resulting patterns (from 2D numerical simulations) for the script-generated geometries tend to exhibit beam directions differing from that desired by ~a few degrees. In fact, the patterns and wave β in the guide are also otherwise non-optimal. At present, we attribute these problems primarily to the imperfect nature of the key approximation that a finite array of non-uniform size wires, with a wave incident in a (in this case, curved) leaky guide, can be represented satisfactorily as a *locally-uniform* wire array subject to an incident *plane wave*. Recall that we found previously that this approximation worked fairly well, not just for the straight channels of a FAWSEA or a CAWSEA (note: CAWSEA curvature minimally impacts individual channel geometries) but also for the bent channels of a BAWSEA. The AAWSEA appears to be less forgiving. Now, this does not mean that AAWSEAs cannot be designed and optimized. Rather, we are simply finding it challenging to prepare *convenient recipes/scripts* to generate/guide those designs.

In consideration of the remaining time and budget, if we do not make more progress on this particular theoretical path shortly, we will instead prepare one or more high-performing representative AAWSEA design examples via "brute-force" numerical methods (2D and 3D), including aperture windows, and will document these particular designs in our reports to serve as representative/useful design references.

3.2. Beam-direction stabilization (compensation for, or suppression of, scanning)

The useful bandwidth associated with delivery of low-VSWR, high-gain, and high peak-power capabilities in a FAWSEA (or similar antenna in this family) can easily exceed +/- 10%. But if one adds a requirement that the beam not appreciably change direction as a function of frequency, usable bandwidth is substantially reduced. Now, this is not usually a serious limitation when employing a source with a *narrow instantaneous* bandwidth (i.e., a frequency relatively-stable throughout a single-pulse or during a rapid-train of output pulses). Indeed, even if such a source is *tunable* (e.g., by +/-10%), the antenna beam simply points in a slightly new (and generally quite-usable) direction once the source is tuned to its new frequency. Rather, the problem we speak of here is if the source output spectra spans significant bandwidth (e.g., +/- 10%) *during a single pulse* or a *rapid-train* of output pulses. Under such conditions, there is no *unique* direction to the output beam, yielding a situation[2] where only a frequency-subset of the radiated power can be oriented toward an intended target.

Consider now a simple 2D FE model of a 2m-long, window-less leaky-wave antenna (L-band example), shown in Figure 2. Note how the beam direction changes with frequency. In Figure 3, we've *added* a set of parallel conducting walls to the same model, *outside* the leaky grill, to constrain direction of the leaked waves and simultaneously enforce local propagation with the *same dispersion relationship* as in the leaky guide (with plate spacing set the same as the effective-height of the leaky guide). This yields nearly-constant electrical-paths for all signals reaching the final aperture, regardless of frequency. Thus, the output beam direction becomes *fixed*. Figure 4 shows a similar arrangement using dielectric (PE) filled channels to shrink the geometry a bit. Some impedance mismatching occurs, but the method still works. We will continue to seek more compact arrangements, perhaps including folding of paths (in 3D) arguably somewhat analogous to the (albeit, shorter-length) curved guide sections in a RAWSEA.

---

[2] This is *not* to be confused with issues arising due to finite antenna fill-time. We are limiting the consideration here to waveforms with pulse-lengths sufficiently long, and frequency variation sufficiently gradual, that effects due to antenna fill-time can be ignored.

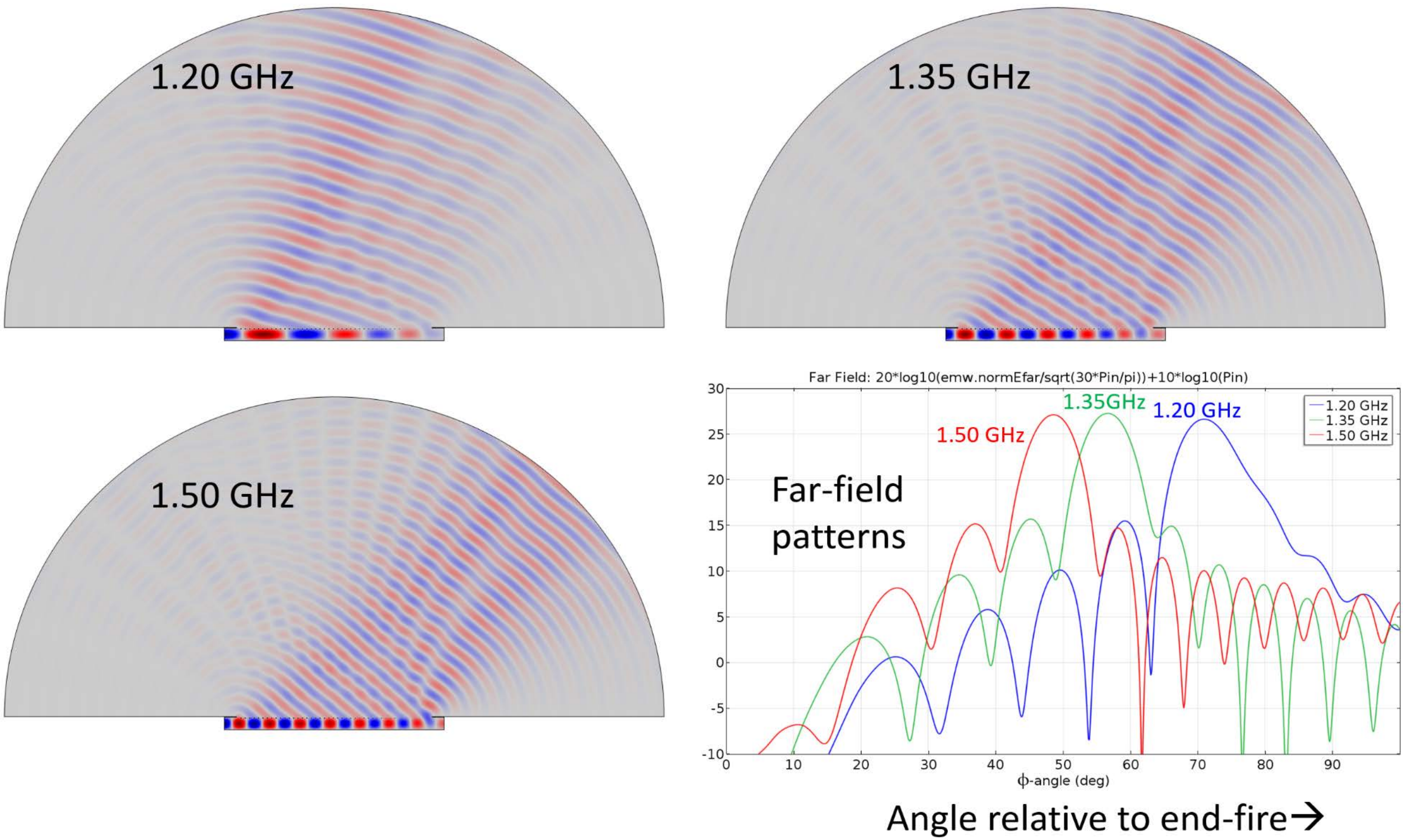


Figure 2. In a forward-traveling leaky-wave antenna, the output beam direction is strongly dependent upon frequency.

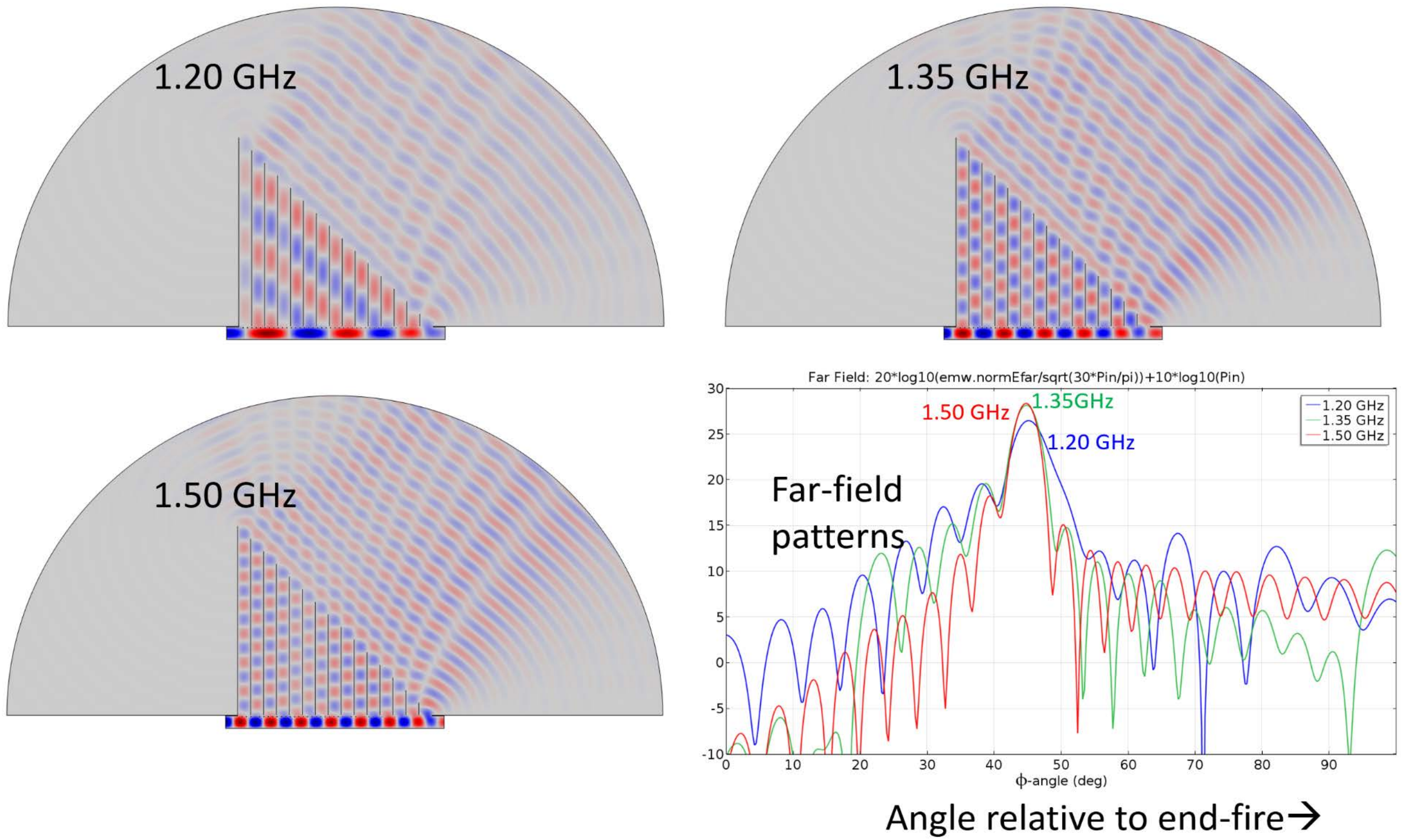


Figure 3. Generating a *fixed-direction* beam is possible via adding a post-leak, compensating-paths structure.

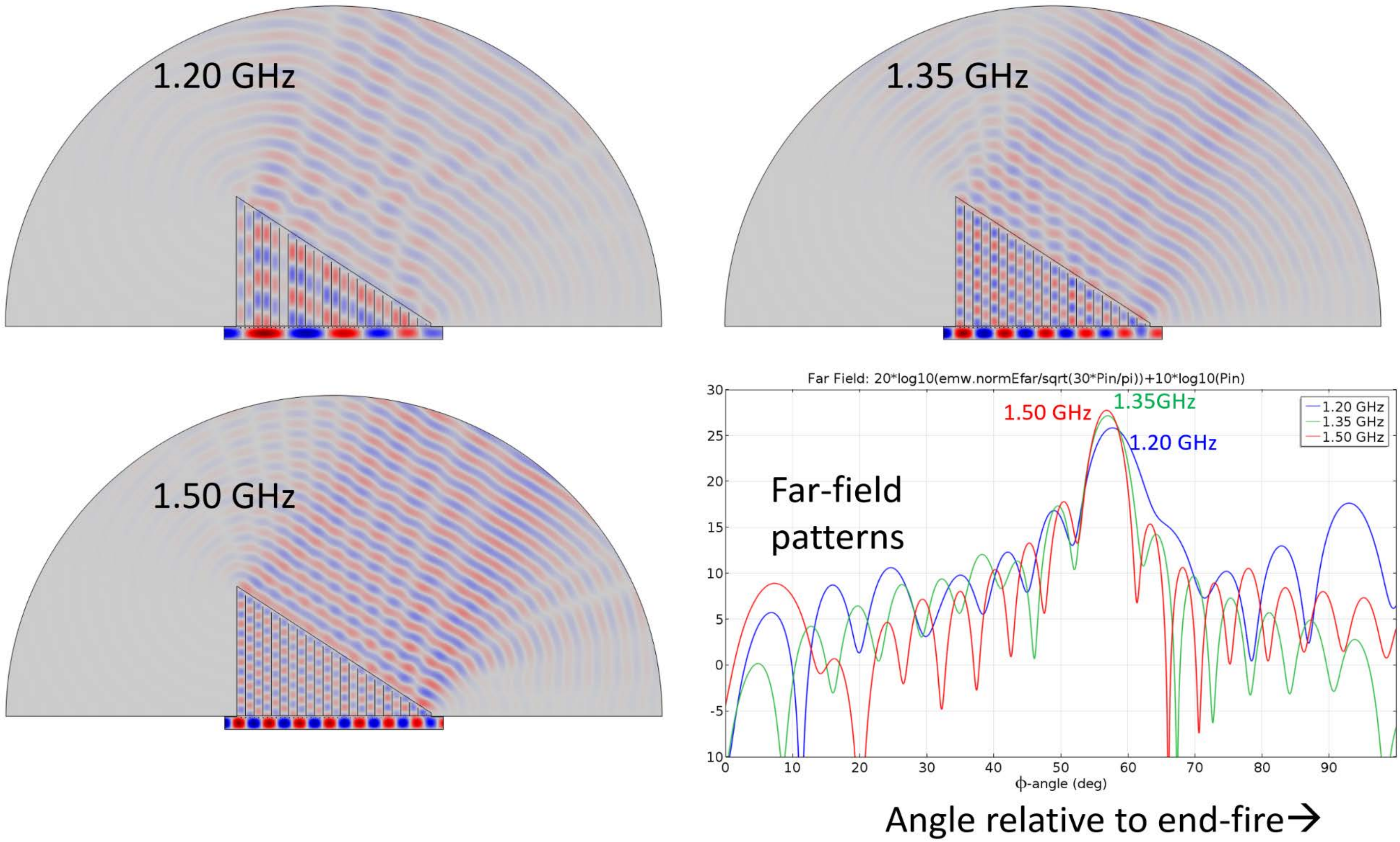


Figure 4. Dielectric (PE)-filling of the compensating structure reduces its required size, but it is still very large. Also, impedance-mismatch issues now more-negatively impact the resulting antenna patterns, an effect that is most visible here in the 1.2 GHz example.

3.3. Presentation at the 18th Annual Directed Energy Symposium

The Directed Energy Professional Society (DEPS)18th Annual Directed Energy Symposium was held in Albuquerque, NM, March 7-11, 2016. SARA's PI, Dr. Robert Koslover, presented an update on our research at the Tuesday-morning session on "HPEM Systems and Technologies." Our presentation title was "Improvements in Low-Profile HPM-Capable Conformable Leaky-Wave Antennas."

We are pleased to report that the number of people attending our presentation was substantial, over-flowing the meeting-room's capacity. Perhaps most notable among those who asked questions or offered comments was Prof. John L. Volakis[3] of Ohio State University, who expressed interest in including some of our work in the next edition of the *Antenna Engineering Handbook*[4], which he edits (currently in its 4th edition). Of course, we welcome such high-profile attention to this research. We have provided Prof. Volakis with copies of the slides from our 2015 & 2016 presentations at DEPS about our research in HPM leaky-wave antennas, and will follow up with him in the future, as appropriate.

For completeness, the slides from our DEPS 2016 presentation are included on the pages that follow.

[3] See http://esl.eng.ohio-state.edu/~volakis/

[4] http://www.amazon.com/Antenna-Engineering-Handbook-Fourth-Edition/dp/0071475745

Improvements in Low-Profile HPM-Capable Conformable Leaky-Wave Antennas

Eighteenth Annual Directed Energy Symposium

March 7-11, 2016

Dr. Robert Koslover (PI)
Mr. Greg Raith
Dr. Sammuel Jalali

Scientific Applications & Research Associates (SARA), Inc.
www.sara.com

Work supported by:

- **Office of Naval Research (ONR), Contract # N00014-13-C-0352.**
- **SARA, Inc. IR&D**

Abstract

We report the latest results of SARA's continuing research in the design and optimization of low-profile, sidewall-emitting, forward traveling-wave, leaky-wave HPM-capable antennas. Subject to surprisingly-few hard constraints, leaky-wave apertures supporting up to multi-GW peak powers are realizable in flat, simply-curved, multiply-curved, and even disconnected/irregularly-shaped forms, thus offering many appealing options for fitting and integrating these antennas into compact HPM-based DEW platforms. Our approach to designing these antennas continues to leverage application of continuous-aperture leaky-wave theory in concert with iterative 2D and 3D full-wave numerical EM models, with which we are growing a catalog of representative antenna configurations that deliver high gain, low VSWR, respectable bandwidth, and other desirable features. Both recent and earlier designs that offer especially-desirable performance characteristics while conforming to geometries of interest are highlighted and discussed.

We gratefully acknowledge the support for this work provided by the Office of Naval Research (ONR) via Contract # N00014-13-C-0352.

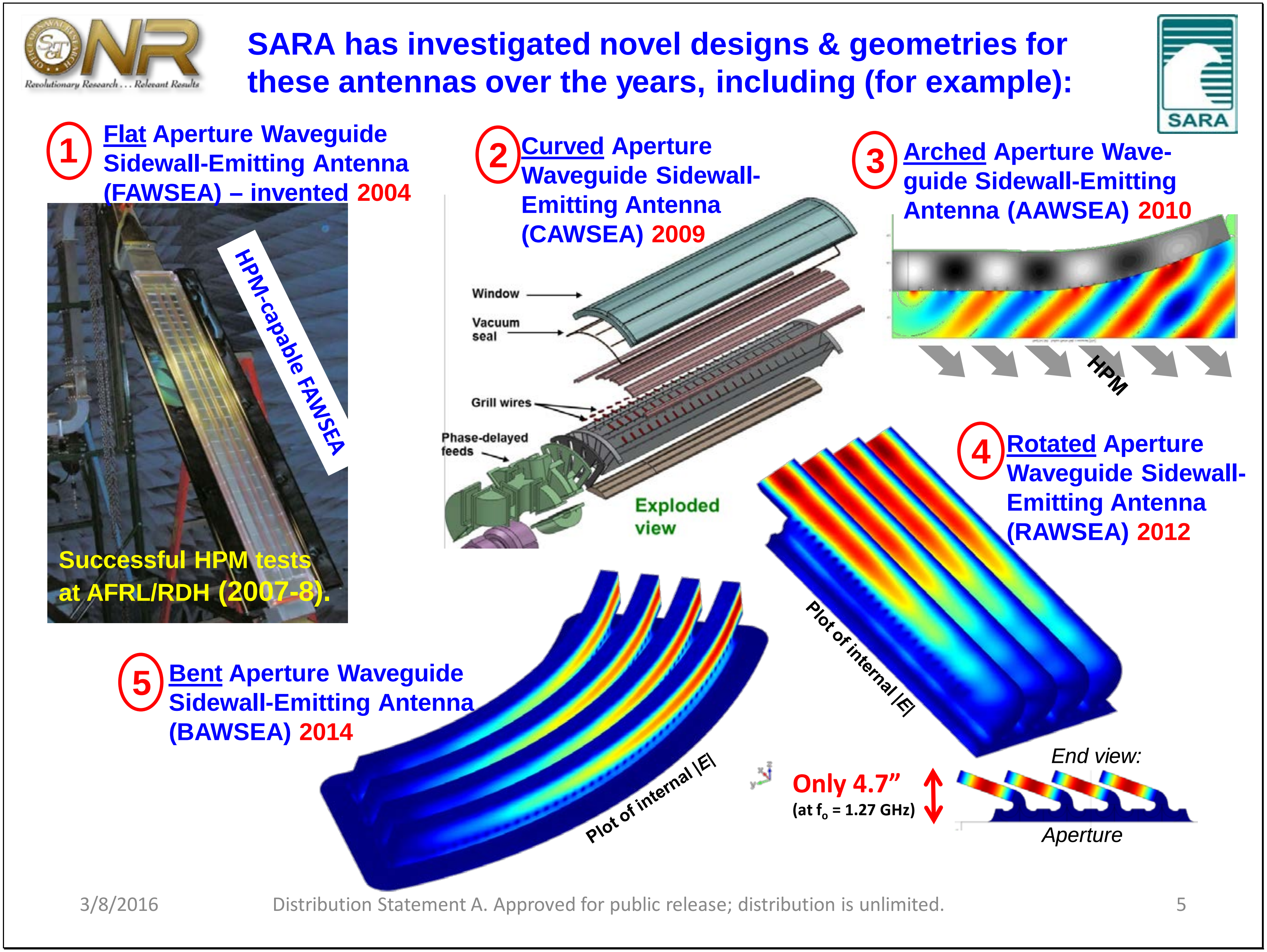
Outline

- **Background:** ***Sidewall-emitting, forward traveling-wave, leaky-wave*** **antennas**
  - **Why use these types of antennas for HPM?**
  - **Operating principles**
  - **Enabling GW-class operation**
  - **Curved-aperture types/naming**
- **Example Designs & Performance**
- **Optimizing field-distributions for curved apertures**
  - **An improved CAWSEA**
- **Extra: How to build a P_{pk}> 1 GW, fully-steerable, high-gain antenna**

Why use sidewall-emitting, forward traveling-wave, leaky-wave antennas in HPM?

- ★ ***Support for extremely high (up to multi-GW) peak power***
- ★ ***High gain and aperture efficiency***
- ★ ***Low-profile*** **(thickness < λ_0)**
- ★ ***Bandwidth sufficient for most HPM sources***
- ★ ***Aperture(s) conformable to flat and curved surfaces***
- ★ ***Customizable aperture sizes and aspect ratios***
- ★ ***Potential for beam-steering***
- ★ ***Rugged and compatible with realistic environments***
- ★ ***No exotic materials required***

continued→



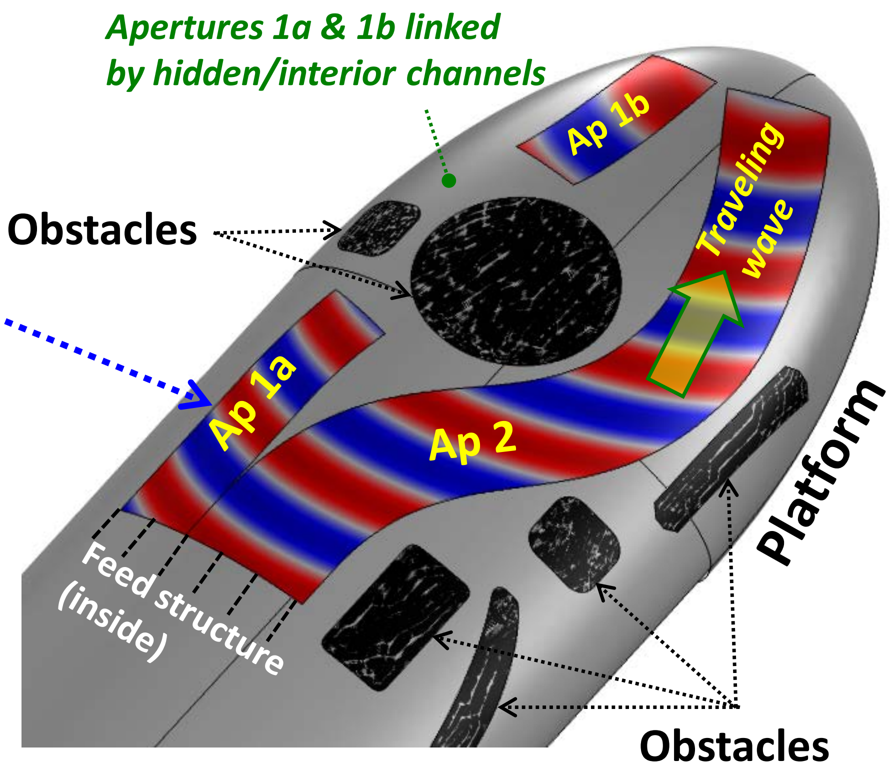
Revolutionary Research . . . Relevant Results
SARA has investigated novel designs & geometries for these antennas over the years, including (for example):
SARA
1 Flat Aperture Waveguide Sidewall-Emitting Antenna (FAWSEA) – invented 2004
HPM-capable FAWSEA
Successful HPM tests at AFRL/RDH (2007-8).
2 Curved Aperture Waveguide Sidewall-Emitting Antenna (CAWSEA) 2009
Window
Vacuum seal
Grill wires
Phase-delayed feeds
Exploded view
3 Arched Aperture Wave-guide Sidewall-Emitting Antenna (AAWSEA) 2010
HPM
4 Rotated Aperture Waveguide Sidewall-Emitting Antenna (RAWSEA) 2012
Plot of internal |E|
End view:
Only 4.7”
(at f_o = 1.27 GHz)
Aperture
5 Bent Aperture Waveguide Sidewall-Emitting Antenna (BAWSEA) 2014
Plot of internal |E|
3/8/2016
Distribution Statement A. Approved for public release; distribution is unlimited.
5

Generalization to fit almost arbitrary surfaces

Generalized Aperture Waveguide Sidewall-Emitting Antenna **(GAWSEA) combines curvatures typical of CAWSEA, AAWSEA, and/or BAWSEA, to fit a *distributed* aperture to a platform and deliver maximum power density to the target.**

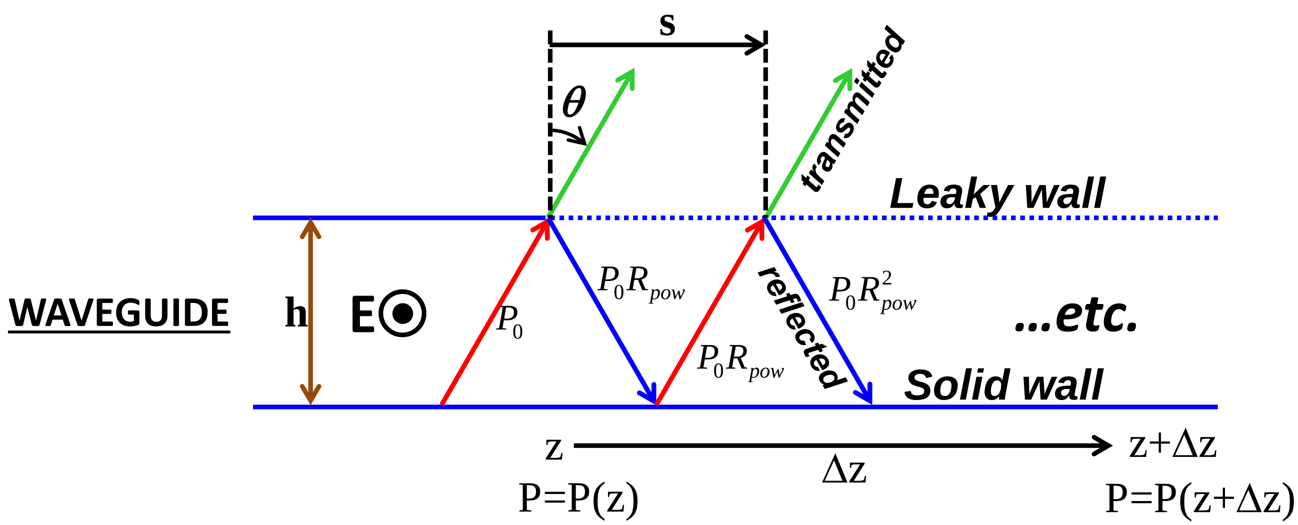
GAWSEA

Aperture customized to fit the platform's surface and curvature while avoiding obstacles and phased to match a radiated plane wave. (Notional Example)



Basics: Traveling wave leaks through leaky-waveguide sidewall

- TE_{10} mode → Interpret as two plane waves reflecting from the walls at an angle θ.
- Replace one sidewall with a partially-transmitting wire grill (wires parallel to E)
- Let T_{pow} = 1-R_{pow} = power *fraction* leaking through *per reflection*.



(Simplified analyses)

For TE_{10}: $s = 4h^2/\lambda_g$, $\lambda_g = \lambda_0/\sin\theta$, and $\cos\theta = f_c/f$, where f_c is the cutoff frequency: $f_c=c/2h$.

The power in the guide *remaining* at the distance z+Δz is given by: $P_{z+\Delta z} = P_z R_{pow}^{\Delta z/s}$

since $\Delta z/s$ = the number of bounces between z and z+Δz. In the limit as Δz→0, this becomes:

The classic equation for attenuation →

$$\boxed{\frac{1}{P(z)}\frac{dP}{dz} = -\alpha(z)}$$ with $$\boxed{\alpha(z) = -\frac{\lambda_g}{4h^2}\ln\left(R_{pow}\right)}$$

continued→

Understanding *uniform* leaky grills *via equivalent circuits*

- Transmission & reflection of TE & TM-incident planewaves at infinite, uniform, arrays of grill wires are discussed in the *Waveguide Handbook* (N. Marcuvitz, 1951.)
- Marcuvitz employed an approximate equivalent-circuit transmission-line (TL) model*. (Others have added various correction terms and expanded on it.)
- R.C. Honey (1959) used these methods with much success with his "Flush-Mounted Leaky-Wave Antenna."
- ~Earliest work on this subject: H. Lamb, "On the Reflection and Transmission of Electric Waves by a Metallic Grating," Proc. London Math. Soc., v. 29, pp. 523-544; 1898.
- Research on leaky-wave antennas leveraging "Partially Reflecting Surfaces" (PRS) continues to the present day.

*More recent papers call this circuit-centric approach the "Transverse Equivalent Network" (TEN) method.

286 *GRATINGS AND ARRAYS IN FREE SPACE* [SEC. 5·21

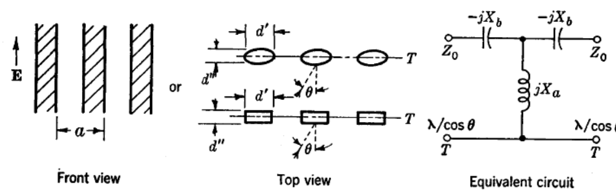


FIG. 5·21-1.

Equivalent-circuit Parameters.—At the terminal plane T

$$\frac{X_a}{Z_0} = \frac{a\cos\theta}{\lambda}\left\{\ln\frac{a}{2\pi r_0} + \frac{1}{2}\sum_{\substack{m=-\infty\\ m\neq 0}}^{\infty}\left[\frac{1}{\sqrt{m^2 + \frac{2ma}{\lambda}\sin\theta - \left(\frac{a\cos\theta}{\lambda}\right)^2}} - \frac{1}{|m|}\right]\right\}, \quad (1a)$$

$$\frac{X_a}{Z_0} \approx \frac{a\cos\theta}{\lambda}\left[\ln\frac{a}{2\pi r_0} + 0.601(3 - 2\cos^2\theta)\left(\frac{a}{\lambda}\right)^2\right], \qquad \frac{a}{\lambda} \ll 1, \quad (1b)$$

$$\frac{X_b}{Z_0} = \frac{a\cos\theta}{\lambda}\left(\frac{2\pi r_1}{a}\right)^2, \quad (2a)$$

where, if $d = (d' + d'')/2$,

$2r_0 = d,$	$2r_1 = \sqrt{dd''}$	for elliptical cross section,
$2r_0 = d,$	$2r_1 = d$	for circular cross section,
$2r_0 = \frac{d'}{2} f_0\left(\frac{d''}{d'}\right),$	$2r_1 = \frac{d''}{\sqrt{2}} f_1\left(\frac{d''}{d'}\right)$	for rectangular cross section.

The functions f_0 and f_1 are defined in Eqs. (8) and (9) of Sec. 5·11c (with $d_0 = 2r_0$, $d_1 = 2r_1$).

Restrictions.—The equivalent circuit is valid for wavelengths and incident angles in the range $a(1 + \sin\theta)/\lambda < 1$. Equations (1a) and (2a) were calculated by a variational method assuming for the obstacle current an angular distribution that is a combination of an even constant function and an odd sine function. The equivalent radii r_0 have been obtained by an equivalent static method. These results, valid only in the small-obstacle range, are estimated to be in error by less than 10 per cent for the range plotted in the accompanying figures.

(Borrowed from N. Marcuvitz, *Waveguide Handbook*)

Extension to *non-uniform* wire grills.

Consider an aperture of length L. To maximize gain & peak-power handling, impose:
(1) All the power to radiate from the guide in length L; and
(2) Uniform leakage (to yield uniform |E| on aperture)

$$\frac{dP}{dz} = -\frac{P_0}{L} \quad \rightarrow \quad P(z) = P_0\left(1 - \frac{z}{L}\right)$$

But, from before, $\frac{1}{P(z)}\frac{dP}{dz} = -\alpha(z)$

Solving for α: $\boxed{\alpha_{ideal}(z) = \frac{1}{L-z}}$

But recall: $\alpha(z) = -\frac{\lambda_g}{4h^2}\ln(R_{pow})$

Combining these, yields: $\boxed{R_{pow,ideal} = \exp\left(-\frac{4h^2}{\lambda_g(L-z)}\right)}$

In summary, we now have:

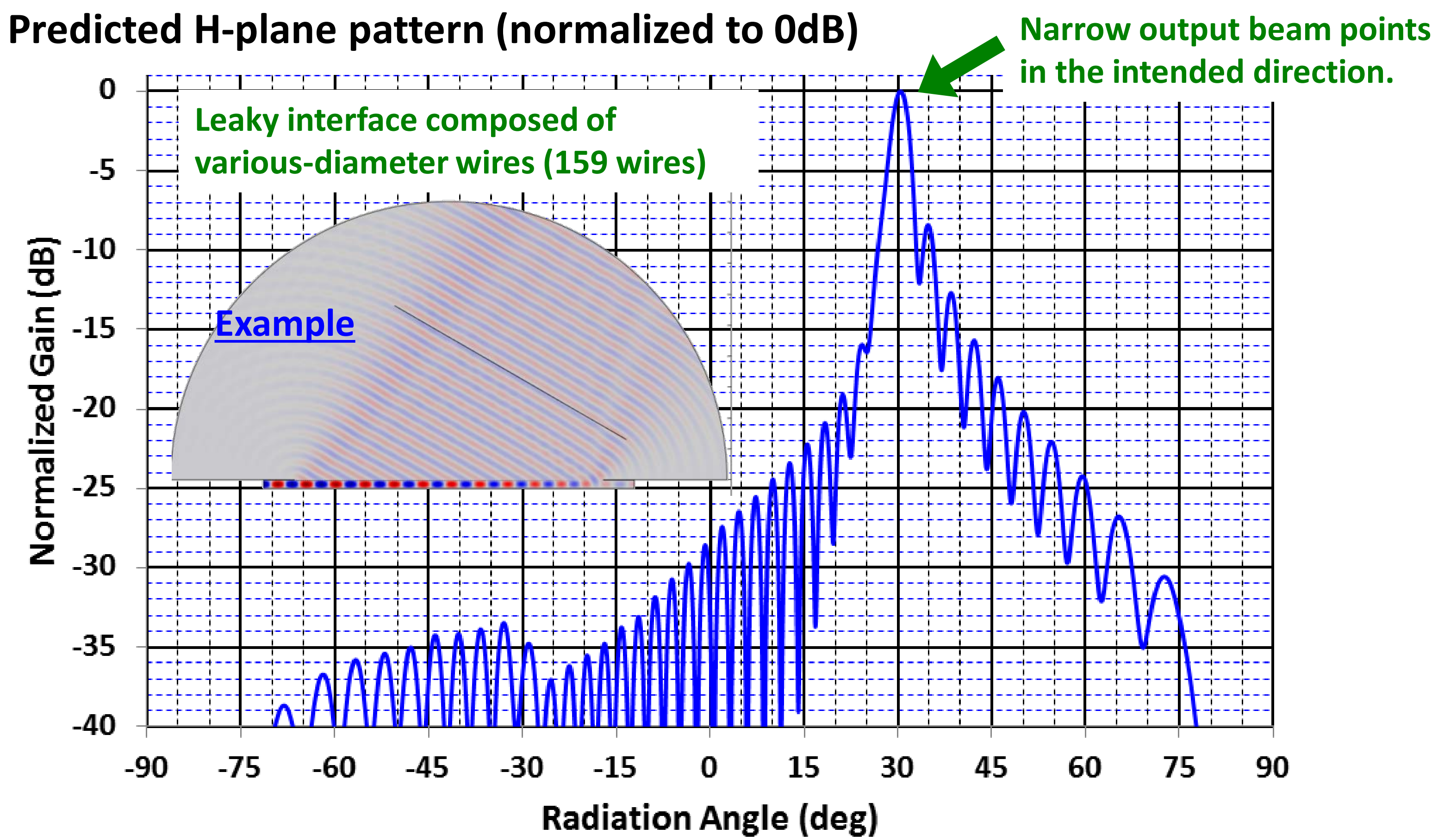
1. R_{pow} as a function of wire diam, spacing, angle of incidence, and frequency.
2. The *desired* R_{pow} (aka, $R_{pow,\ ideal}$) for optimal gain & P_{pk} handling in a leaky guide.

→ Set R_{pow} (θ, a, d, f, z) = $R_{pow,ideal}$ (L,h,z), solve for the undetermined variables to yield a starting-set (wire sizes, spacing) for the leaky grill, then optimize further*.

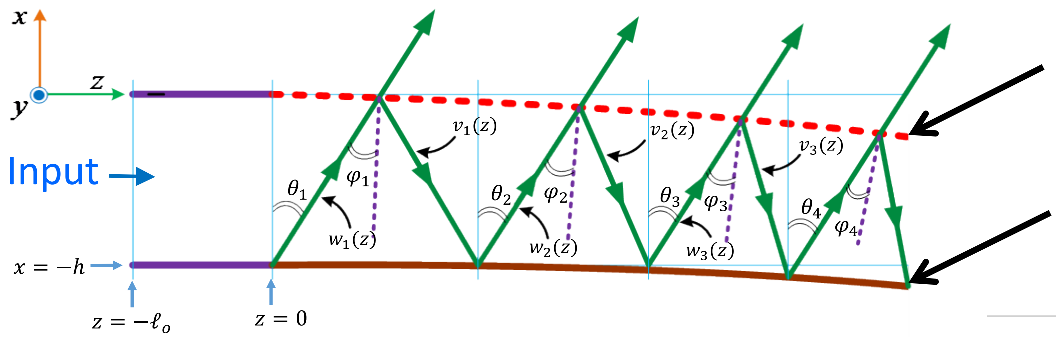
*Additional and more detailed theoretical treatment including accounting for interfaces, aperture-curvature, etc. is provided in the periodic technical reports delivered under ONR Contract # N00014-13-C-0352.

continued→

Example: 2D finite-element model using a wire-grill generated via the aforementioned approach.



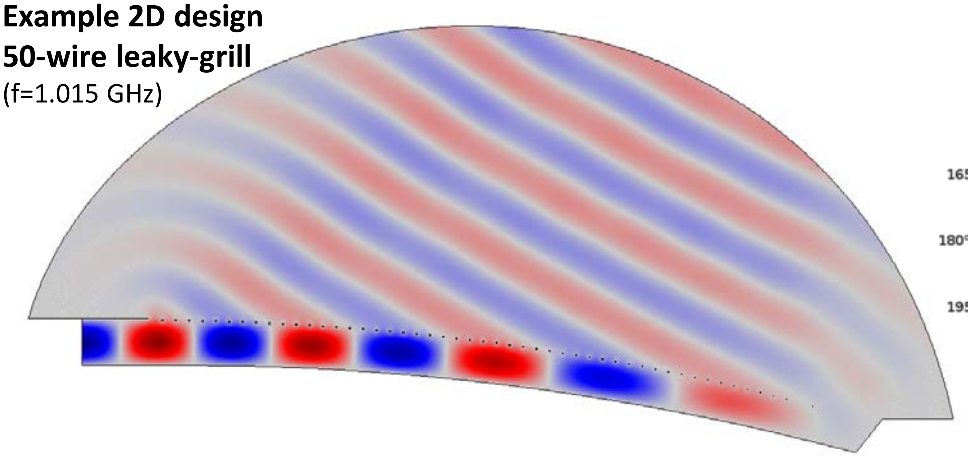
The analyses we used to define the FAWSEA grill wires can be extended* to guide the design of arched (AAWSEA) configurations.

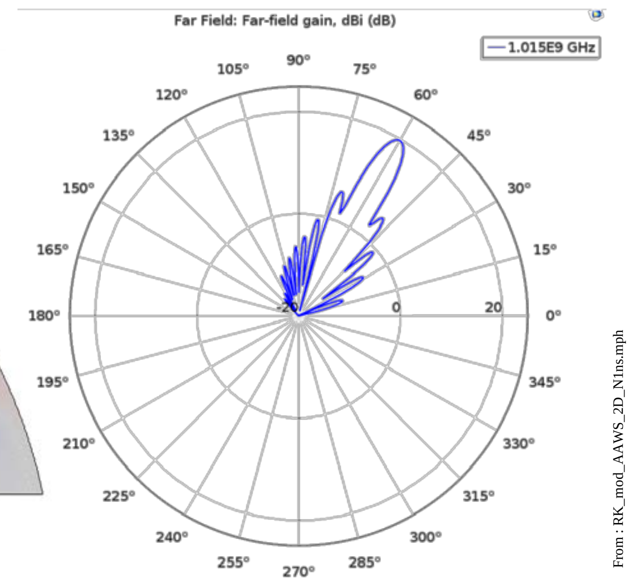


Desired conformal geometry. Grill designed for uniform power out.

Opposite wall. Curvature chosen to preserve the fixed-angle output beam

Example 2D design
50-wire leaky-grill
(f=1.015 GHz)





*See the periodic technical reports delivered under ONR Contract # N00014-13-C-0352.

Enabling HPM operation

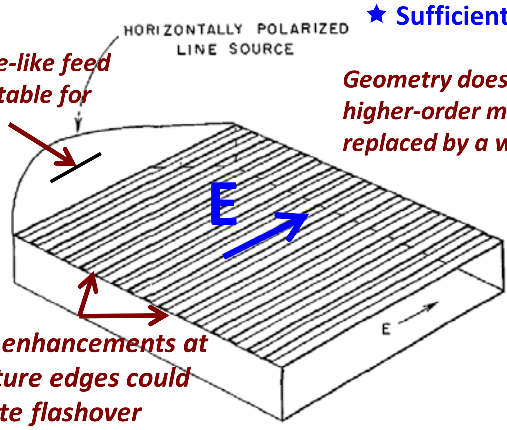
Classic designs from the literature are *not* immediately-suitable for HPM:

Flat aperture

- ★ Low profile
- ★ Wide range of areas and aspect ratios
- ★ Sufficient bandwidth

Dipole-like feed unsuitable for HPM

Geometry does not reject higher-order modes, if feed is replaced by a waveguide



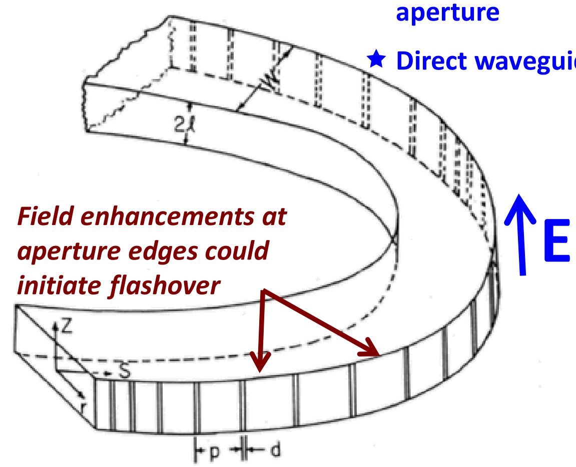
Field enhancements at aperture edges could initiate flashover

Adapted from: Honey, R.C., "A Flush-Mounted Leaky-Wave Antenna with Predictable Patterns," *IRE Trans. Antennas and Propagat.*, 7, pp. 320-329, 1959.

Aperture curved in H-plane

- ★ Conforms to a curved aperture
- ★ Direct waveguide-feed

Field enhancements at aperture edges could initiate flashover



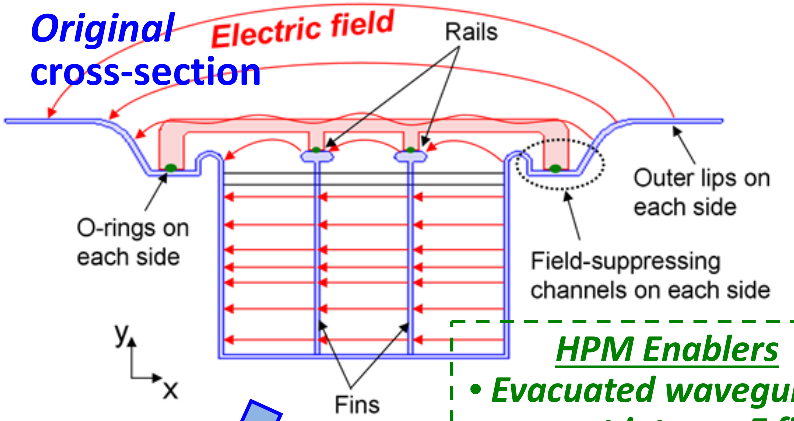
From: Ishimaru, A., and F. R. Beich, "Pattern Synthesis With a Flush-Mounted Leaky Wave Antenna on a Conducting Circular Cylinder," *J. Research of The Nat. Bureau Of Standards-D. Radio Propagat.* <u>66</u>, No.6, pp. 783-796, Nov-Dec, 1962.

…but the <u>concepts</u> they embody are extendable to GW-class HPM antennas.

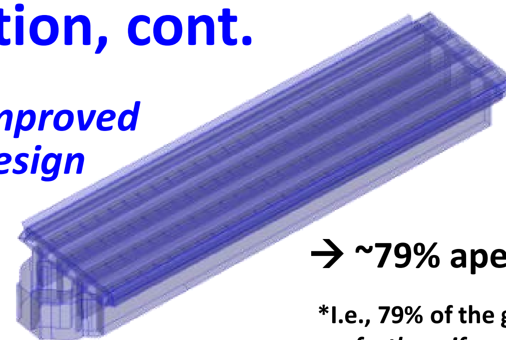
continued→

Enabling HPM operation, cont.

***Original* cross-section**



Improved design

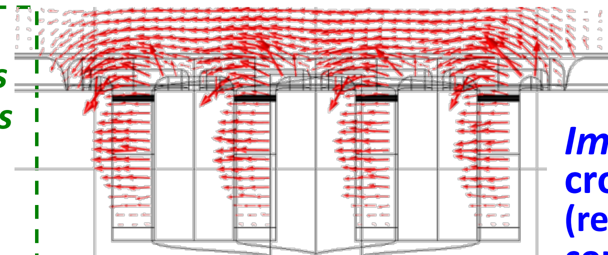


→ ~79% aperture efficiency*

***I.e., 79% of the gain arising from a *perfectly-uniform* amplitude and phase across the aperture.**

HPM Enablers

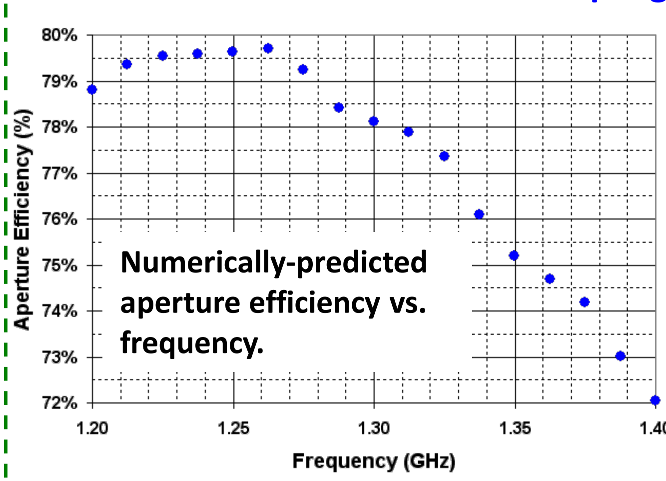
- ***Evacuated waveguides support intense E fields***
- ***Aperture edges ⊥ to E are external to the leaky grill, rounded, and under vacuum***
- ***Leaky wire grill is parallel to E, so no field enhancements there.***
- ***Division into multiple channels suppresses higher-order modes.***
- ***E at triple points is strongly suppressed by recessed tracks and symmetry.***



***Improved* cross-section (reduces cross-coupling)**

P_{pk} goal for this 1st HPM prototype was 400 MW.

<u>Tested up to 542 MW</u> (at AFRL/RDH) No arcs or breakdown.



Numerically-predicted aperture efficiency vs. frequency.

Distribution Statement A. Approved for public release; distribution is unlimited.

Curved Aperture Types/Naming

SARA's growing family of low-profile, forward-traveling, fast-wave, leaky-wave HPM antennas now includes:

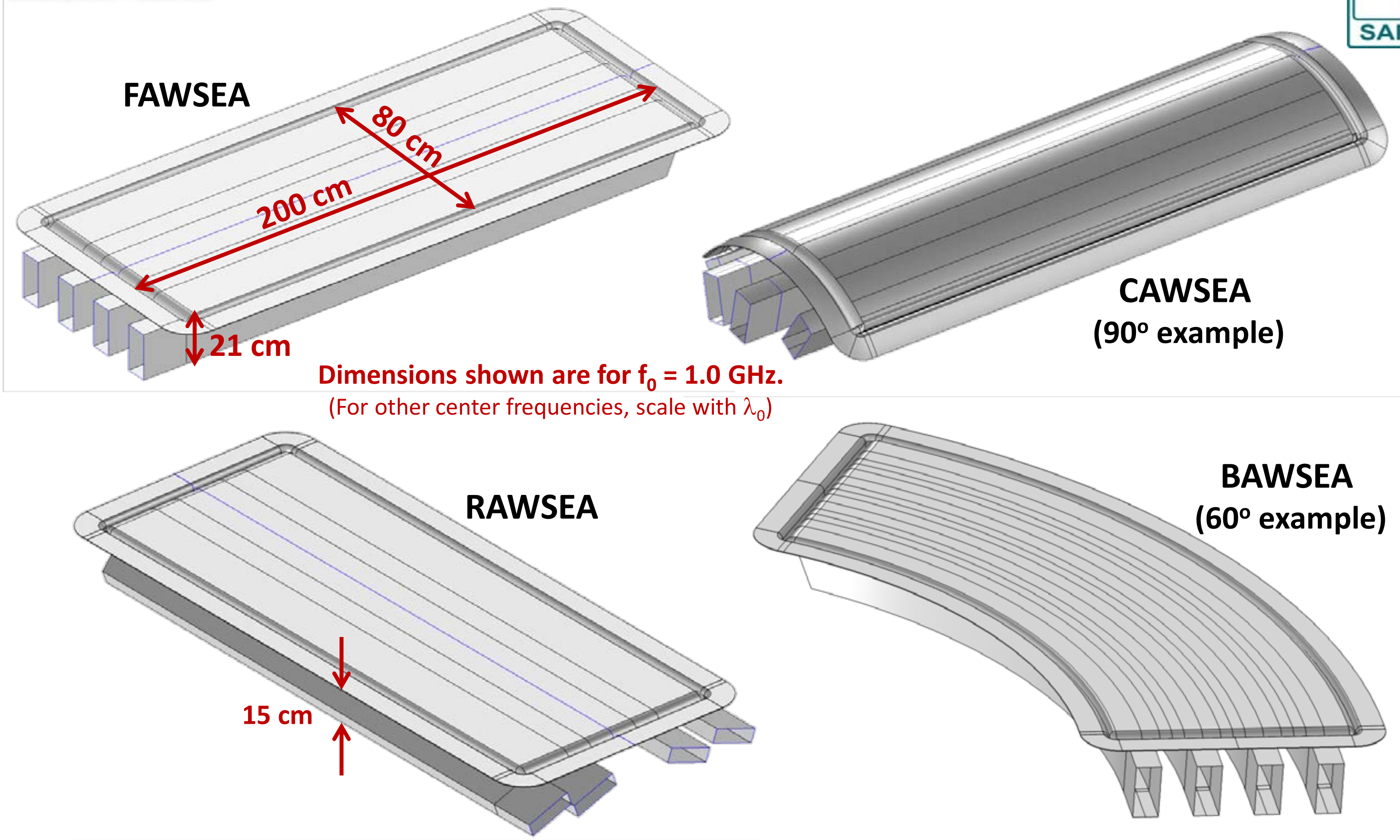
2004 → 2016

Acronym	Full Name	Identifying Geometry / Feature(s)
FAWSEA	**Flat** Aperture Waveguide Sidewall-Emitting Antenna	Flat linear aperture, parallel straight channels.
CAWSEA	**Curved** Aperture Waveguide Sidewall-Emitting Antenna	Aperture curved in E-plane. Curvature may be compensated via delays introduced at feeds.
AAWSEA	**Arched** Aperture Waveguide Sidewall-Emitting Antenna	Aperture curved in H-plane. Curvature may be compensated via varying β along guides.
RAWSEA	**Rotated** Aperture Waveguide Sidewall-Emitting Antenna	The leaky channels are tilted relative to the aperture, notably reducing the antenna's depth.
PAWSEA	**Pinched** Aperture Waveguide Sidewall-Emitting Antenna	Double- or triple-curved aperture customized to conform to part or all of an ogive (nose cone).
BAWSEA	**Bent** Aperture Waveguide Sidewall-Emitting Antenna	Aperture curved in the aperture plane. Curvature compensated via varying β along guides.
GAWSEA	**Generalized** Aperture Waveguide Sidewall-Emitting Antenna	An aperture with multiple-curvatures or complex topology. Curvature and topology compensated via delays at feeds, varying β along guides, imbalanced power division among channels, etc.

Outline

- **Background:** ***Sidewall-emitting, forward traveling-wave, leaky-wave*** **antennas**
  - **Why use these types of antennas for HPM?**
  - **Operating principles**
  - **Enabling GW-class operation**
  - **Curved-aperture types/naming**
- **Example Designs & Performance**
- **Optimizing field-distributions for curved apertures**
  - **An improved CAWSEA**
- **Extra: How to build a P_{pk}> 1 GW, fully-steerable, high-gain antenna**

Some examples* of practical 4-channel designs

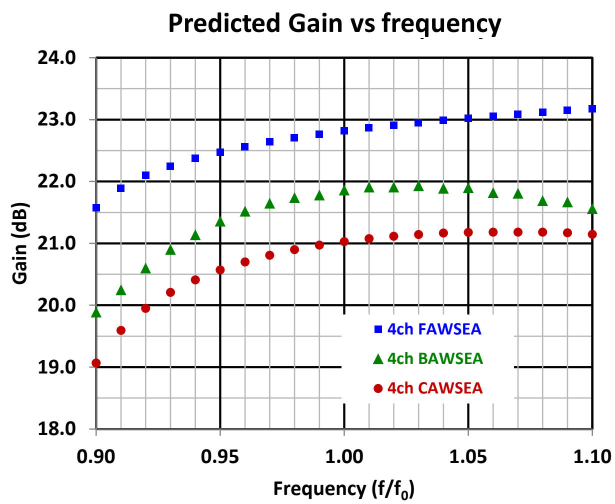


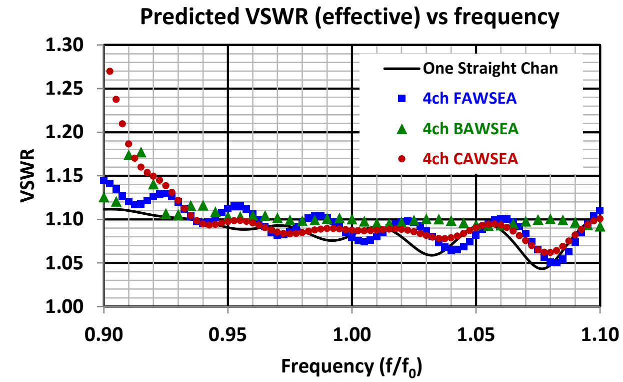
Dimensions shown are for f_0 = 1.0 GHz.
(For other center frequencies, scale with λ_0)

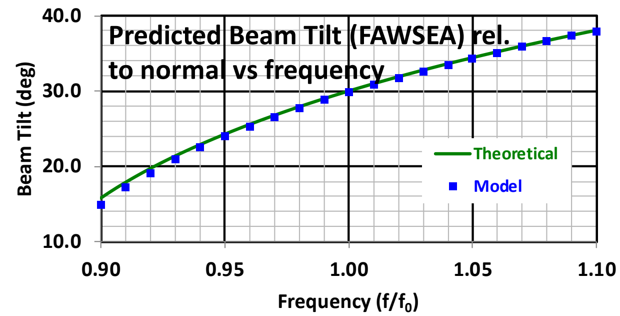
*For detailed design/geometry information, please refer to the periodic technical reports delivered to date under ONR Contract # N00014-13-C-0352.

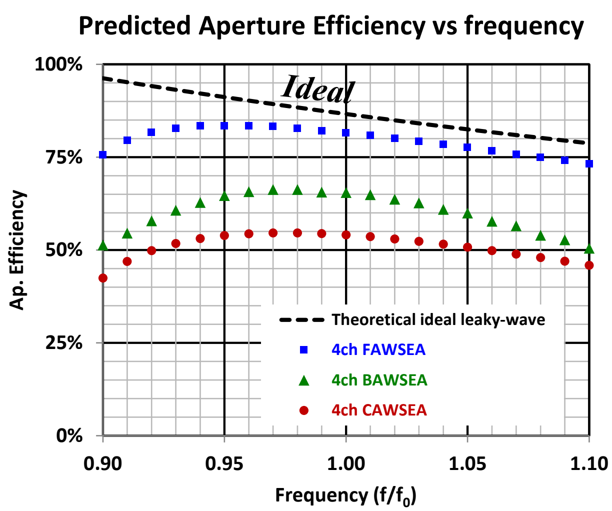
continued→

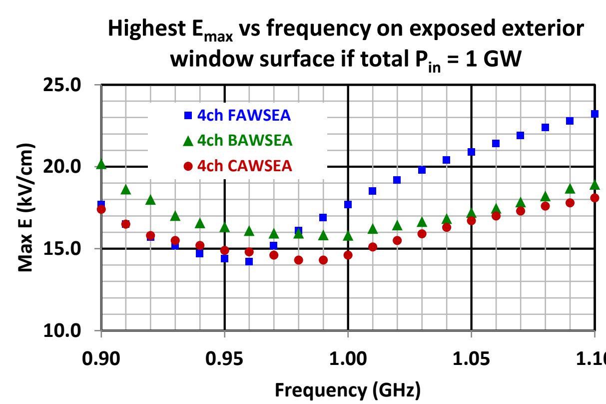
Comparing FAWSEA, BAWSEA, & CAWSEA with ~same aperture areas.





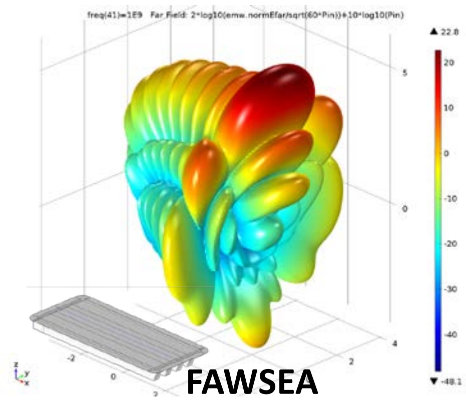


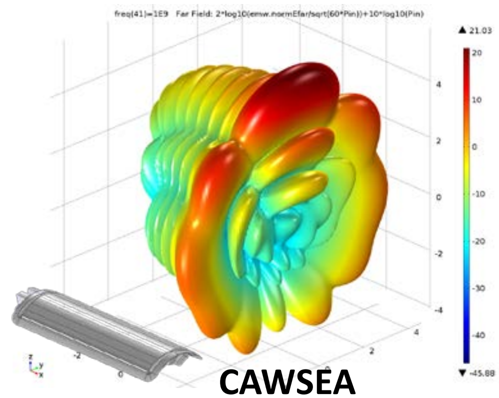


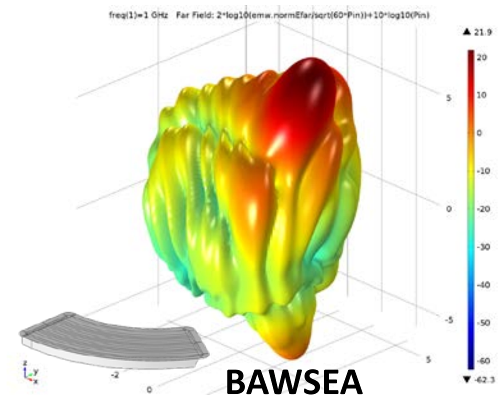


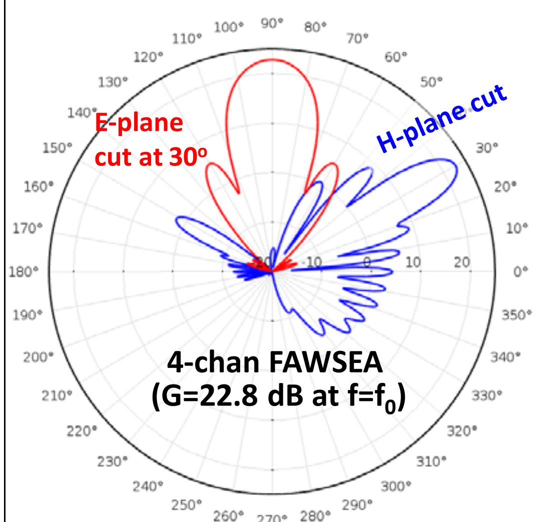
Examples of practical designs, cont.

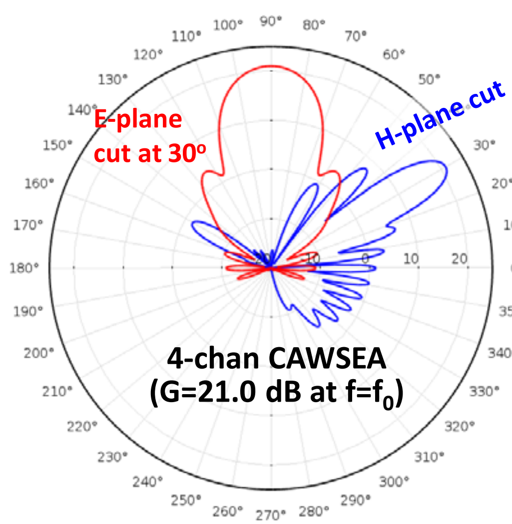
Computed 3D patterns and principal-plane cuts at $f=f_0$

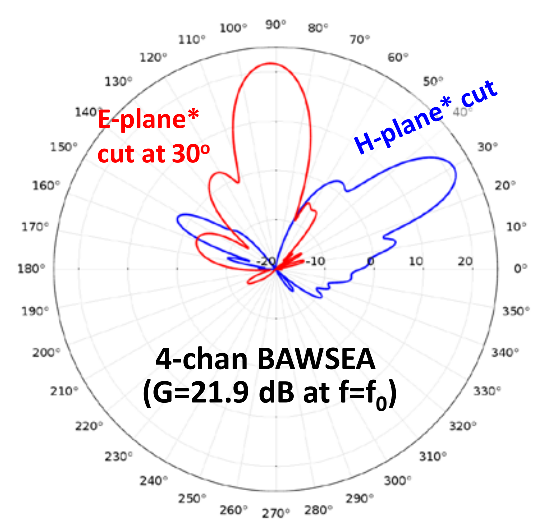












Outline

- **Background:** ***Sidewall-emitting, forward traveling-wave, leaky-wave*** **antennas**
  - **Why use these types of antennas for HPM?**
  - **Operating principles**
  - **Enabling GW-class operation**
  - **Curved-aperture types/naming**
- **Example Designs & Performance**
- **Optimizing field-distributions for curved apertures**
  - **An improved CAWSEA**
- **Extra: How to build a P_{pk}> 1 GW, fully-steerable, high-gain antenna**

Optimizing field-distributions for curved apertures

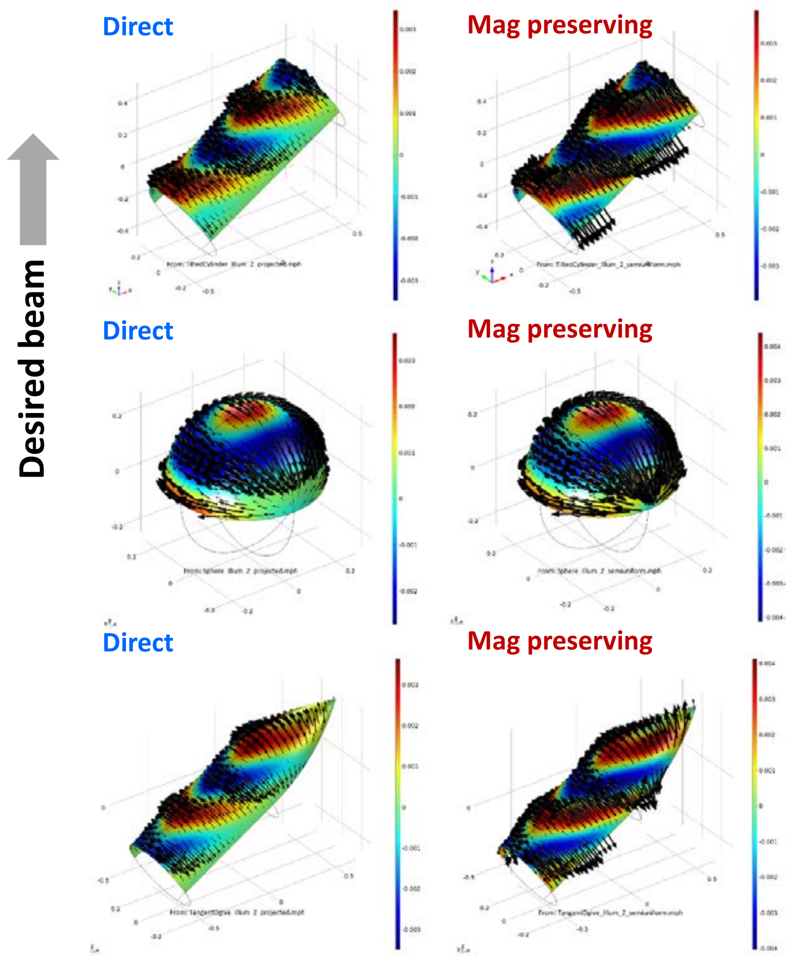
Q: What's the best way to distribute E across a curved-surface, to radiate a high-gain beam?

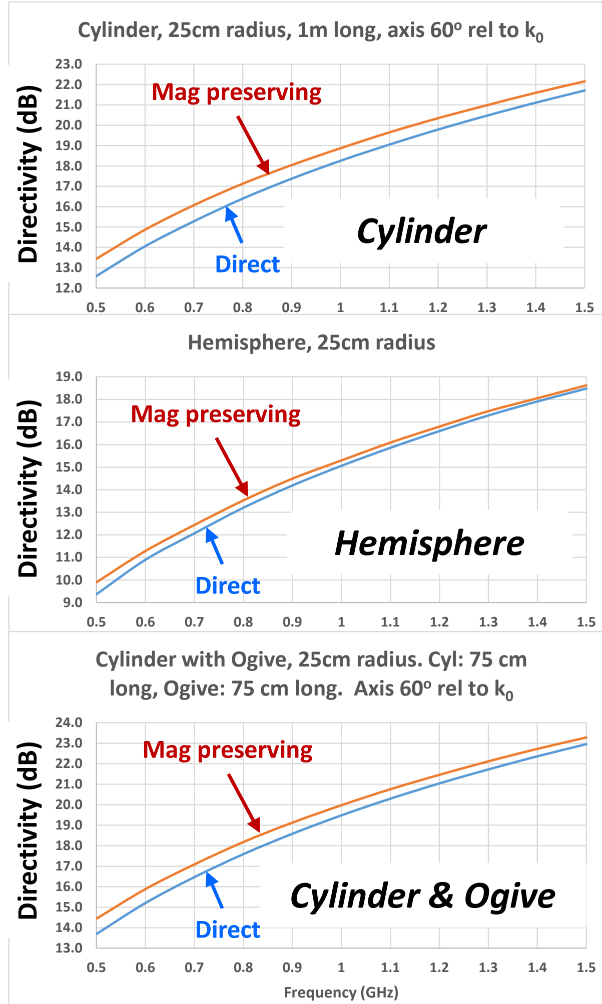
A: There is *more than one way* to "back-project" a to-be-radiated plane-wave (E_{pl}) to "match" a surface-tangential aperture (E_{ap}). The three methods below all yield E_{ap} distributions matching the *phase* of a plane wave:

Type of Projection	Why consider it?	Equation (yields purely surface-tangential E_{ap})	Effect upon $\lvert\vec{E}_{ap}\rvert$	Impact on surface breakdown risk
Direct	Simple & reasonable	$\vec{E}_{ap} = \vec{E}_{pl} - \hat{n}(\hat{n}\cdot\vec{E}_{pl})$	$\lvert\vec{E}_{ap}\rvert$ strongest where the surface is *best directed* to generate the desired beam.	**LOW RISK**
Magnitude-preserving	Best for peak-power handling	$\vec{E}_{ap} = \dfrac{\vec{E}_{pl} - \hat{n}(\hat{n}\cdot\vec{E}_{pl})}{\lvert\vec{E}_{pl} - \hat{n}(\hat{n}\cdot\vec{E}_{pl})\rvert} E_0$	$\lvert\vec{E}_{ap}\rvert$ is uniform.	**LOWEST POSSIBLE RISK**
Magnitude-enhancing	Speculation about achieving higher gain	$\vec{E}_{ap} = \dfrac{\vec{E}_{pl} - \hat{n}(\hat{n}\cdot\vec{E}_{pl})}{\lvert\vec{E}_{pl} - \hat{n}(\hat{n}\cdot\vec{E}_{pl})\rvert^2} E_0$	$\lvert\vec{E}_{ap}\rvert$ strongest where the surface is most-poorly oriented to generate the desired beam, to attempt to compensate.	**Large $\lvert E_{ap}\rvert$ in some places → INCREASED RISK.**

Optimizing field-distributions for curved apertures, cont.

We used numerical models to explore directivity achievable with idealized surfaces:





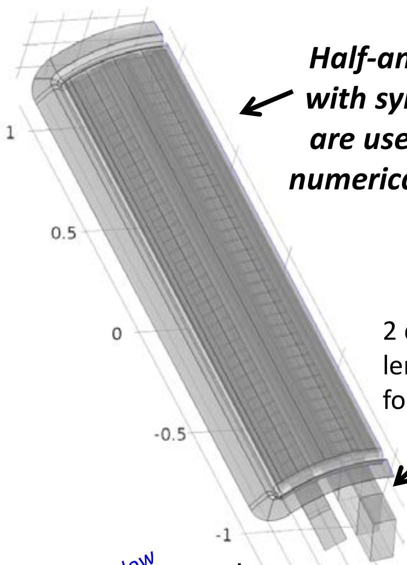
→ **The "Magnitude Preserving" projection yields greater directivity, in all three examples.**

The preceding curved-aperture analyses suggested the possibility of:

An *improved* CAWSEA (to fit a fixed-radius cylinder)

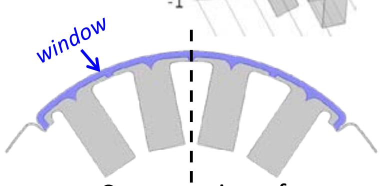
4-chan CAWSEA$_{90}$ vs. 16-chan CAWSEA$_{180}$ (new!)

(presented at DEPS in 2015)



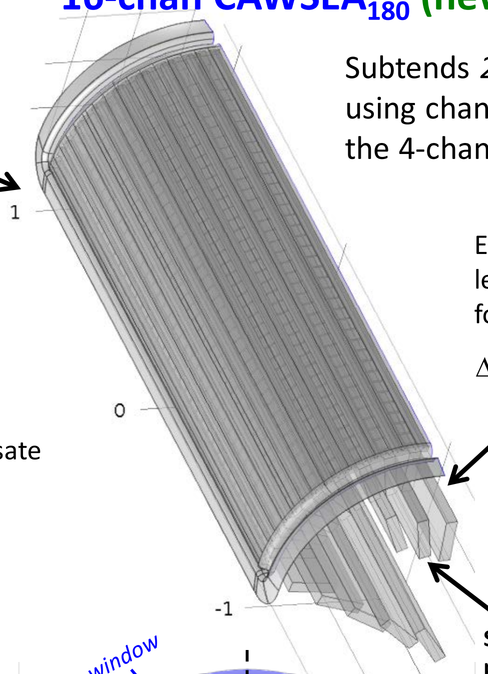
Half-antennas, with symmetry, are used in the numerical models

2 different feed lengths compensate for phase error



Cross-section of 4-chan CAWSEA$_{90}$ (from our earlier "recommended" design)

From: FourChan_Std_CAWSEA_5e_Optfor1GHz_phdelayed.mph



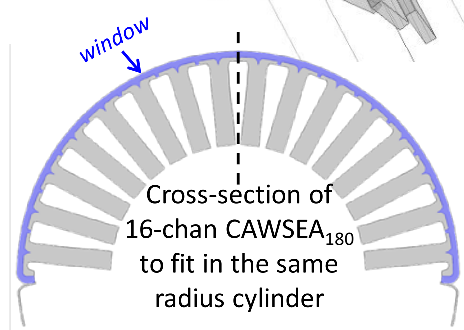
Subtends *2x azimuthal angle*, using channels *half as wide* as the 4-chan CAWSEA.

Employs 8 different feed lengths ΔL_n to compensate for phase error.

$$\Delta L_n = \frac{k_0}{k_g} R \cos\phi_n \sin\theta$$

ϕ_n = n^{th} azim angle from ctr
θ = tilt of axis rel to z
k_0 = free wavenumber at f_0
k_g = guide wavenumber at f_0.
R = cyl radius to aperture

Shorter here due to computed phase correction > 360°, so we can subtract one guide wavelength.



Cross-section of 16-chan CAWSEA$_{180}$ to fit in the same radius cylinder

{Note: We need 16 instead of 8 channels to make this work, to support the larger gradients in phase required at large azimuthal angles.}

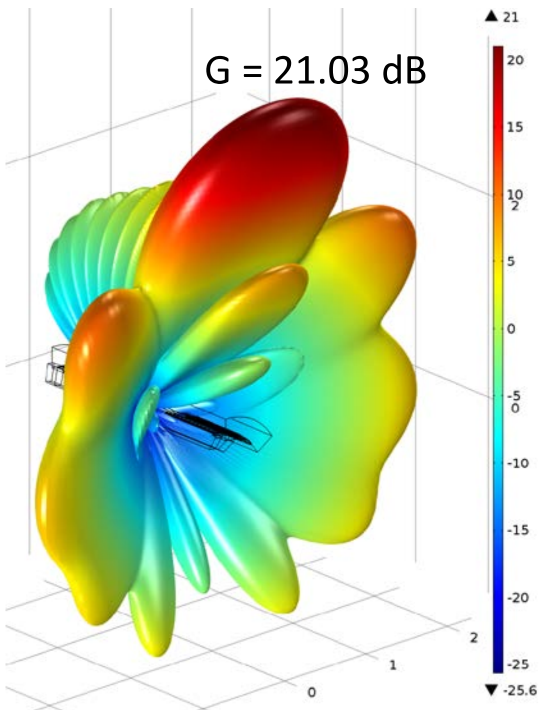
From: Rev2_ThinChan_CAWSEA_180_comp_phased.mph

continued→

An Improved CAWSEA, cont.

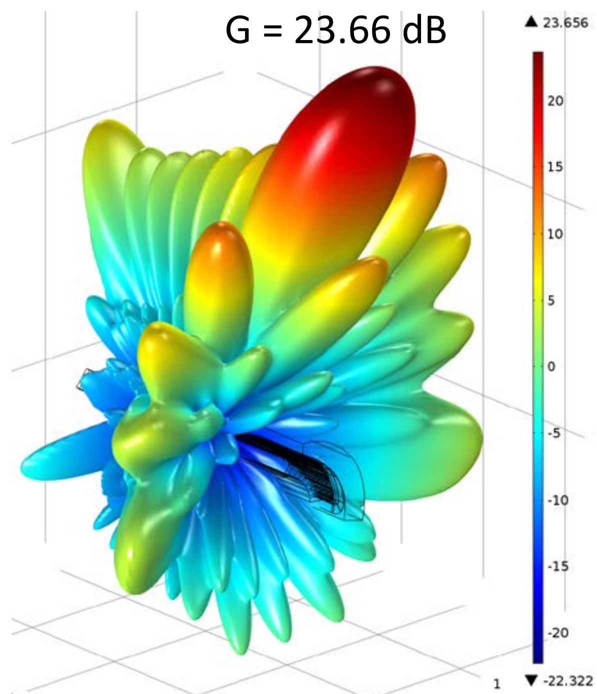
Computed 3D gain patterns at f_0=1.0 GHz. Phase-compensated CAWSEAs

(RF model outline included to clarify antenna orientation.)



4-chan CAWSEA$_{90}$

From: FourChan_Std_CAWSEA_5e_Optfor1GHz_phdelayed.mph



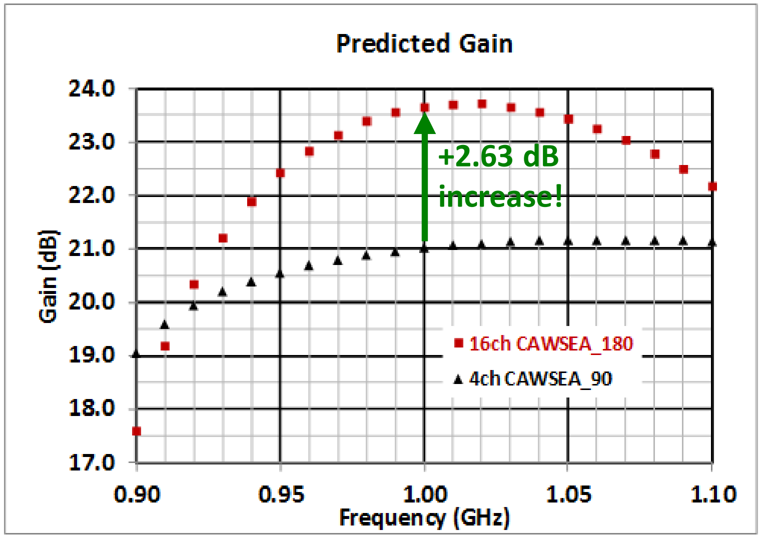
16-chan CAWSEA$_{180}$

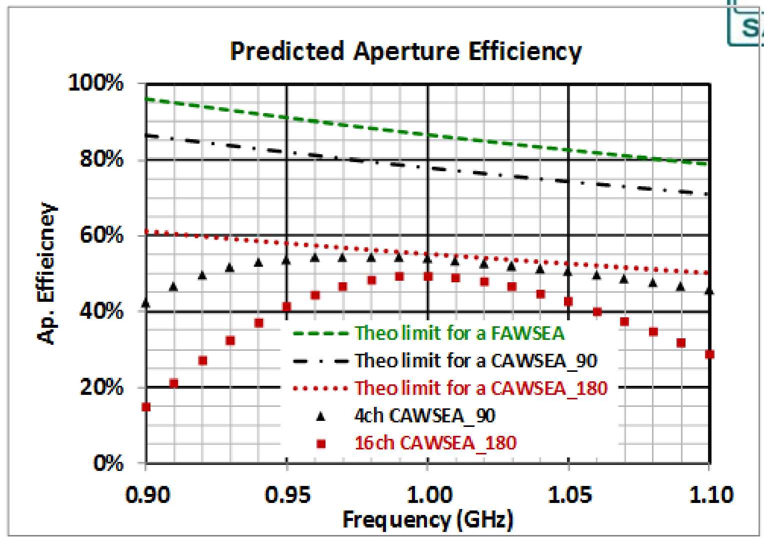
From: Rev2_ThinChan_CAWSEA_180_comp_phased.mph

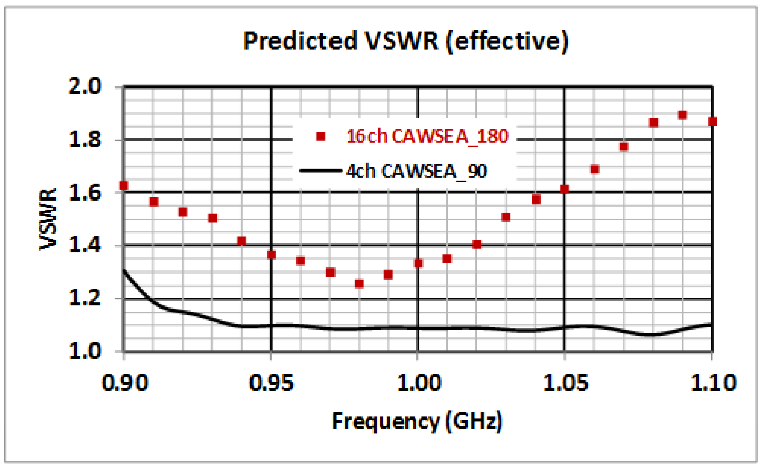
→That's +2.63 dB more gain. And the new antenna fits into the *same diameter cylinder*.

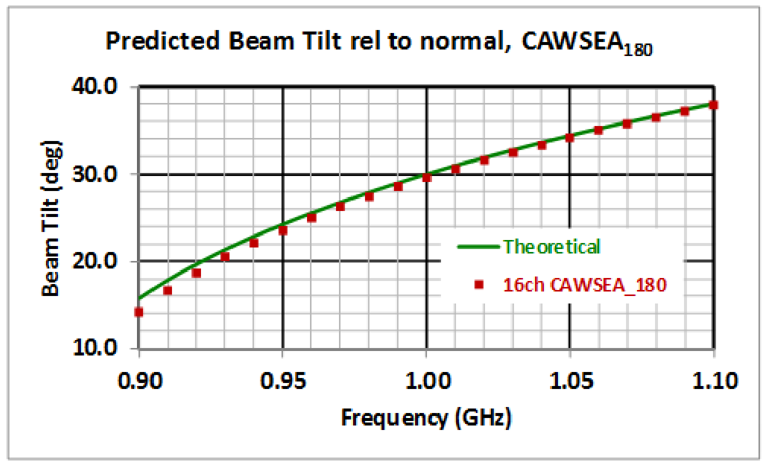
continued→

An Improved CAWSEA, cont.









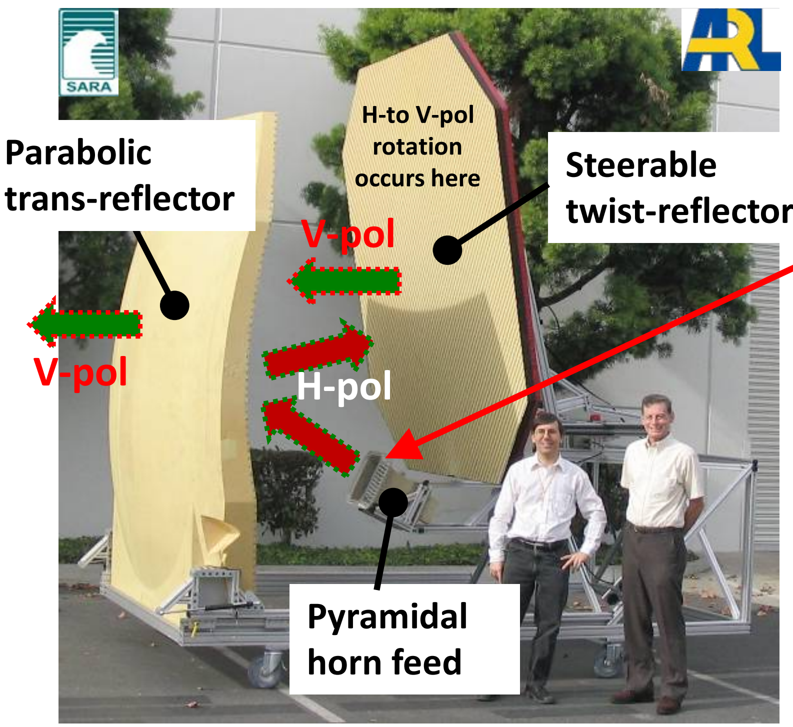
From: ThinChan_CAWSEA_180_notes.xlsx

Outline

- **Background:** ***Sidewall-emitting, forward traveling-wave, leaky-wave*** **antennas**
  - **Why use these types of antennas for HPM?**
  - **Operating principles**
  - **Enabling GW-class operation**
  - **Curved-aperture types/naming**
- **Example Designs & Performance**
- **Optimizing field-distributions for curved apertures**
  - **An improved CAWSEA**
- **Extra: How to build a P_{pk}> 1 GW, fully-steerable, high-gain antenna**

Extra: How to build a P_{pk}> 1 GW, fully-steerable, high-gain antenna

<u>Background</u>: Over a decade ago, SARA developed "The world's first truly-steerable HPM antenna"



US Patent No. 6,559,807, May 6, 2003.
Work supported by US Army/ARL Contract # DAAD17-01-C-0071.

- G~29dB (L-band).
- Very widely-steerable in azimuth and elevation.

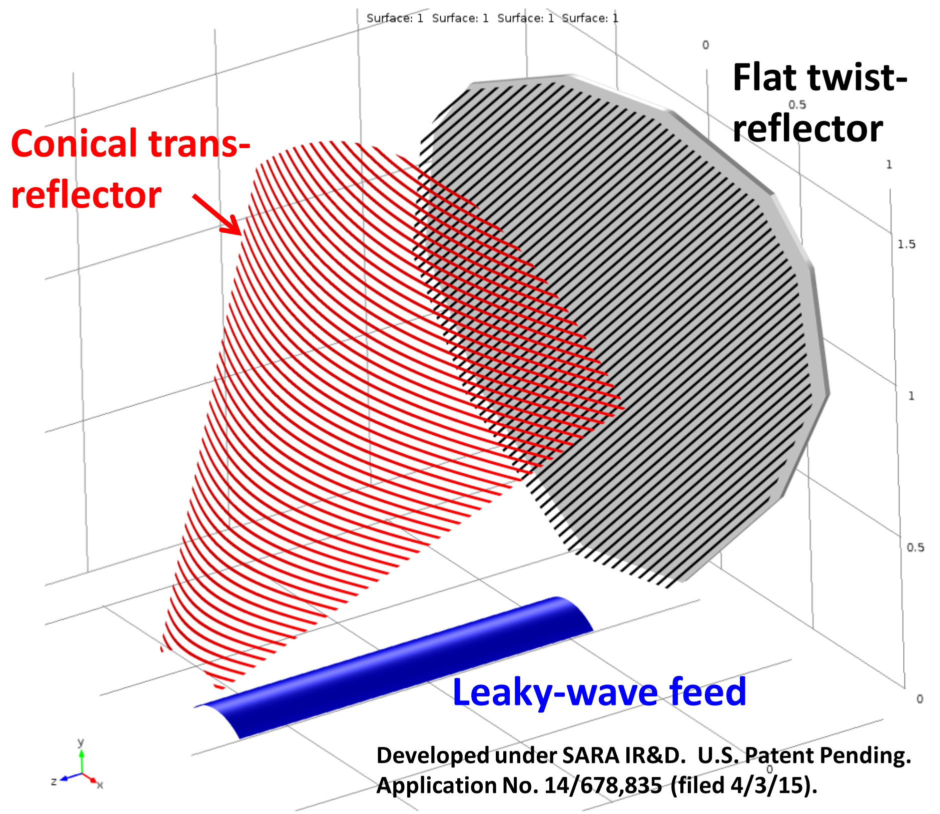
Risk of air/surface breakdown at the feed <u>constrained operation to about 100-200 MW peak.</u>

So… what if you want to operate at P_{pk} > 1 GW?

continued→

Extra: How to build a P_{pk}> 1 GW, fully-steerable, high-gain antenna, cont.

1. Replace the pyramidal horn feed with a suitable GW-class FAWSEA or CAWSEA.
2. Replace the offset *parabolic* trans-reflector with suitable offset *conical* trans-reflector.



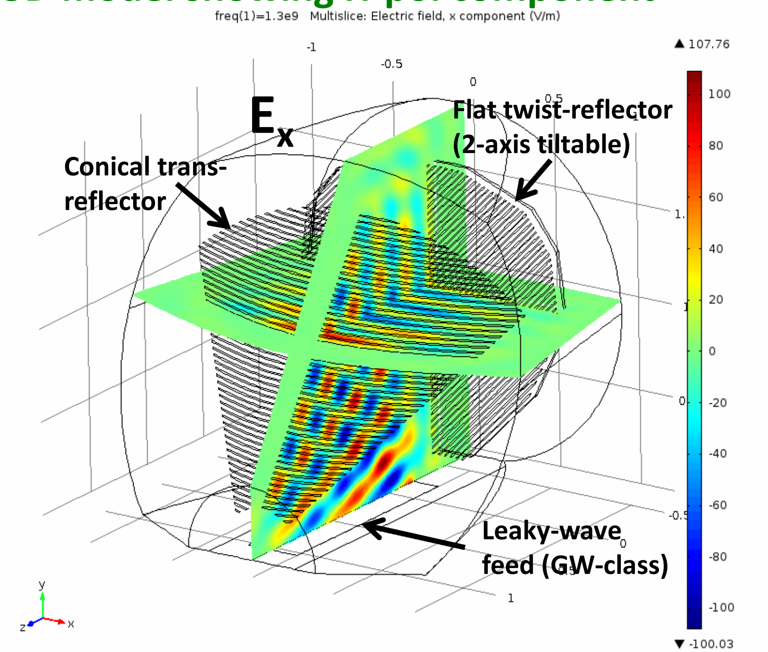
Developed under SARA IR&D. U.S. Patent Pending. Application No. 14/678,835 (filed 4/3/15).

continued→

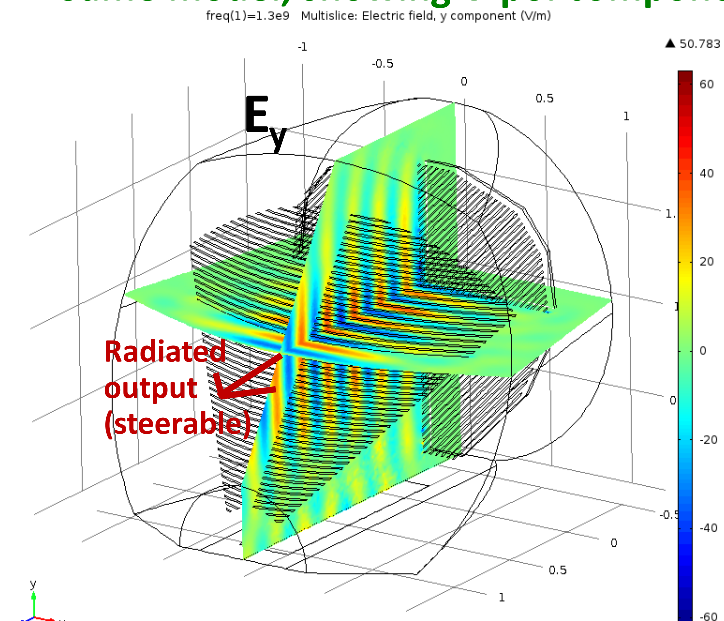
Extra: How to build a P_{pk}> 1 GW, fully-steerable, high-gain antenna, cont.

Result → A *fully-steerable, GW-class, high-gain* antenna!

3D model showing H-pol component



Same model, showing V-pol component



Developed under SARA IR&D. U.S. Patent Pending. Application No. 14/678,835 (filed 4/3/15).

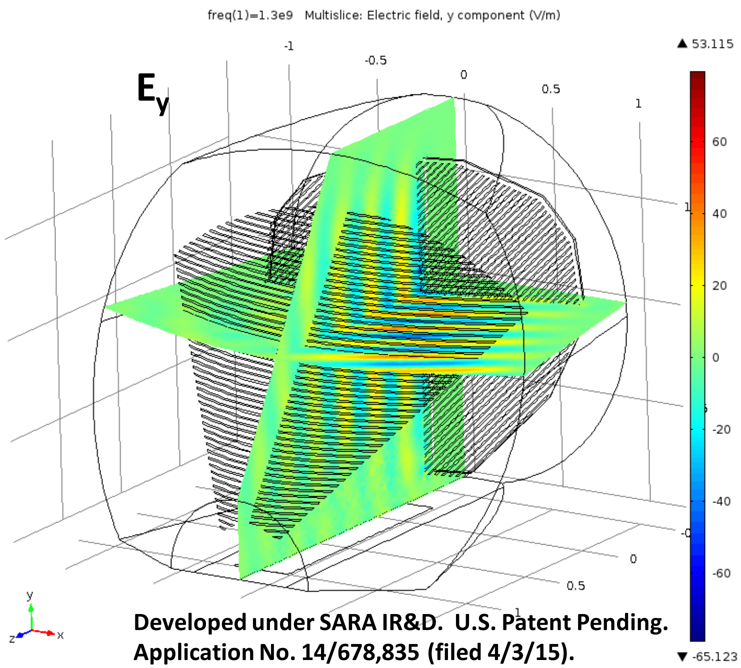
From: Transref_twistref_1.mph

continued→

Extra: How to build a P_{pk}> 1 GW, fully-steerable, high-gain antenna, cont.

Example: Steering the beam by 30° in azimuth (via rotating the twist-reflector 15°) reduces the predicted gain by only 0.18 dB relative to the un-steered case.

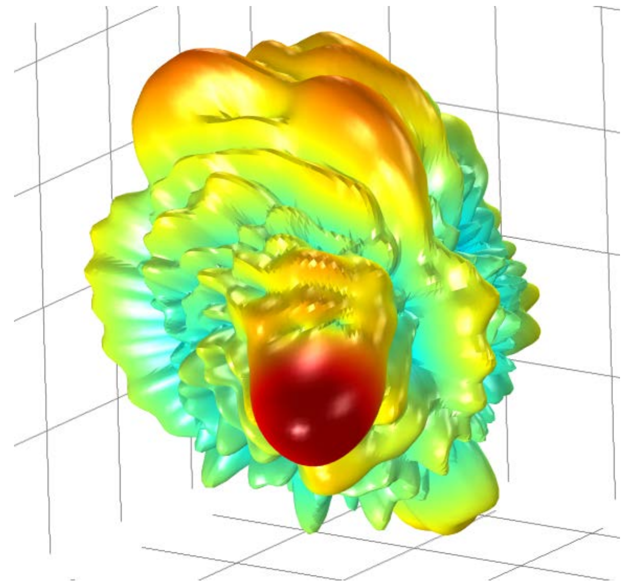
3D numerical model



Developed under SARA IR&D. U.S. Patent Pending. Application No. 14/678,835 (filed 4/3/15).

Steered 3D pattern

The "pencil beam" is well-preserved.



For more information…

At SARA

Dr. Robert Koslover
Principal Investigator
Ph: (903)565-0389
rkoslover@sara.com

Mr. Sean Ahern
Business Development
Ph: (714)224-4410
sahern@sara.com

At ONR

Joong Kim, PhD
Program Officer, Code 30
Office of Naval Research
Ph: 703-696-4742
joong.kim@navy.mil

Mr. Lee Mastroianni
Expeditionary Maneuver
Warfare and Combating
Terrorism S&T (Code 30)
Ph: (703) 696-3073
lee.mastroianni@navy.mil

At AFRL/RDH

Dr. Andrew Greenwood
Senior Electronics Engineer
AFRL/RDHE
Ph: (505)846-6642
andrew.greenwood@us.af.mil

4. DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

Work performed during this 10th quarter of the R&D program included continuation of our investigation into improved design methods/recipes for the AAWSEA, presentation of our work at the DEPS 18th Annual Directed Energy Symposium, and identification of novel applications and extensions to this technology.

In the coming quarter, we plan to advance and further document the design recipes and our "standard/ recommended" designs for each of the multiple-identified variants of forward-traveling, fast-wave, leaky-wave HPM-capable antennas.

As always, we appreciate ONR's continuing support for this R&D.

BIBLIOGRAPHY (alphabetical)

Bodnar, D.G. and D.T. Paris, “New Variational Principle in Electromagnetics,” *IEEE Trans. Antennas & Propagat*, vol. AP-18, pp. 216-223, 1970

Goldstone, L.O. and Oliner, A.A., “Leaky-Wave Antennas I: Rectangular Waveguides," *IRE Trans. Ant. and Propagat*., Oct., 1959, pp. 307-319.

Goldstone, L.O. and Oliner, A.A., “Leaky-Wave Antennas II: Circular Waveguides," *IRE Trans. Ant. and Propagat*., May., 1961, pp. 280-290.

Honey, R.C., “A Flush-Mounted Leaky-Wave Antenna with Predictable Patterns,” *IRE Trans. Antennas and Propagat*., 7, pp. 320-329, 1959.

Ishimaru, A.K. and Beich, F.R., “Pattern Synthesis With a Flush-Mounted Leaky Wave Antenna on a Conducting Circular Cylinder,” *J. of Res. of the Nat. Bureau of Standards-D. Radio Propagat* Vol. 66D, No.6, Nov- Dec. 1962, pp. 783-796.

Jull, E.V., “Radiation from Apertures,” Chap. 5 of *Antenna Handbook: Theory, Applications, and Design*, Ed. by Y.T. Lo and S.W. Lee, Van Nostrand Reinhold, NY, 1988.

Lewin, L., “Theoretical analysis of the junction discontinuity between a straight and a curved section of rectangular waveguide,” *Proc. IEE,* Vol. 124, pp. 511-516, 1977.

Lewin, L., “The E-plane Taper Junction in Rectangular Waveguide,” *IEEE Trans. Microwave Theory and Techniques*, vol. MTT-27, pp. 560-563, 1979.

Marcuvitz, N., *Waveguide Handbook*, McGraw-Hill, NY, 1951.

Nishida, S., “Coupled Leaky Waveguides I: Two Parallel Slits in a Plane” *IRE Trans. Ant. and Propagat*., May, 1960, pp. 323-330.

Nishida, S., “Coupled Leaky Waveguides II: Two Parallel Slits in a Cylinder,” *IRE Trans. Ant. and Propagat.*, July, 1960, pp. 354-360.

Oliner, A.A. and R.G. Malech, “Radiating Elements and Mutual Coupling,” “Mutual Coupling in Infinite Scanning Arrays,” and “Mutual Coupling in Finite Scanning Arrays,” -- Chaps. 2, 3, and 4 respectively of *Array Theory and Practice*, Vol. II of *Microwave Scanning Antennas*, Ed. by R.C. Hansen, Peninsula Publishing, Los Altos, CA, 1985.

Oliner., A.A, and D.R. Jackson, “Leaky Wave Antennas," Chap. 11 of *Antenna Engineering Handbook*, 4th Ed., Edited by J.L. Volakis, McGraw-Hill, NY, 2007.

Schwinger, J., and D.S. Saxon, *Discontinuities In Waveguides - Notes on Lectures by Julian Schwinger*, Gordon and Breach Science Publishers, NY, 1968.

Silver, S., *Microwave Antenna Theory and Design*, 1st Ed, publ. by office of Scientific Research and Development, National Defense Research Committee, NY, 1949.

SUGGESTED DISTRIBUTION LIST

<u>Official Record Copy</u>
Mr. Lee Mastroianni
E-Mail: lee.mastroianni@navy.mil
Code 30
Office of Naval Research
875 North Randolph St.
Arlington, VA 22203-1995 1 cy

Dr. Joong H. Kim
E-Mail: joong.kim@navy.mil
Code 30
Office of Naval Research
875 North Randolph St.
Arlington, VA 22203-1995 1 cy

Director, Naval Research Lab
E-mail: reports@library.nrl.navy.mil
Attn: Code 5596
4555 Overlook Avenue, SW
Washington, D.C. 20375-5320 1 cy

Defense Technical Information Center
E-mail: tr@dtic.mil
8725 John J. Kingman Road
STE 0944
Ft. Belvoir, VA 22060-6218 1 cy

Dr. Donald Shiffler
AFRL/RDH
Kirtland AFB, NM 87117-5776 1 cy

Dr. Kyle Hendricks
AFRL/RDHP
Kirtland AFB, NM 87117-5776 1 cy

Dr. Andrew D. Greenwood
AFRL/RDHE
Kirtland AFB, NM 87117-5776 1 cy

Dr. Susan Heidger
AFRL/RDH
Kirtland AFB, NM 87117-5776 1 cy

Mr. Matthew McQuage
Naval Surface Warfare Center
Dahlgren Division, Q07
Dahlgren, VA 22448 1 cy

Michael Wagaman
Advanced Technology Directorate
PEO Strike Weapons and Unmanned Aviation
Patuxent River, MD. 1 cy

Dr. Frank E. Peterkin
Director
Directed Energy Technology Office
17320 Dahlgren Road
Naval Surface Warfare Center
Dahlgren, VA 22448 1 cy

LTC Charles Ormsby
Chief
Directed Energy Requirements
Langley AFB, VA 1 cy

Patrick Randeson
Science, Technology and Weapons Analyst
Central Intelligence Agency
Washington, D.C. 1 cy